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TERTIARY STRATIGRAPHY AND SEDIMENTATION IN THE GEELONG-MAUDE AREA, VICTORIA

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Abstract

Shallow shelf sedimentation occurred in many parts of southern Victoria, including the Geelong area, during Tertiary time. A complete marine cycle of deposition is represented commencing with basal sands and passing to shallow-water limestones (calcarenites) developed during Oligo-Miocene trangression. In late Batesfordian time (L. to M. Miocene) considerable deepening of the sea occurred associated with maximum transgression. Granite islands were submerged and a widespread change from limestone to an argillaceous facies developed.

Stable conditions continued into Bairnsdalian (U. Miocene) with the sea becoming ever shallower due to slow infilling of the basin. Uplift in U. Miocene led to shallow seas and considerable submarine erosion, accompanied by the formation of a widespread phosphatic nodule bed. The nodules are, in part, reworked concretions, formed in the underlying sediment and concentrated during later erosion. A thin cover of shallow-water sands with marine fossils overlies them.

During the main sedimentary cycle, minor local regression occurred W. of the Rowsley Fault enabling basalt to be extruded over Janjukian (U. Oligocene) marine sediments near Maude. This was followed by erosion and transgression across the basalt surface with the disconformable accumulation of the Upper Maude Limestone.

In the transgressive deposits, formation boundaries are diachronous and strong environmental control of faunas is often evident. Some time-rock correlations are tentatively suggested.

Throughout the Tertiary, the location of shoreline in the Geelong region was controlled by tectonic lineaments. A succession of movements is postulated along an E.-W. line N. of Maude with downwarping of the basin in the S. and uplift in the N.

Introduction and Previous Work

The area selected for study is situated on the W. margin of the Port Phillip basin and provides an opportunity to study an almost complete marine cycle of sedimentation commencing with the Oligo-Miocene transgression and terminating in Pliocene regression.

Many previous workers have contributed to the knowledge of the area but for the most part their studies have been palaeontological rather than stratigraphical. Some of the rock units have become widely known because of the rich Tertiary faunas they contain, e.g. the Batesford Limestone. The most important contributions to the geology of the area have been made by Hall and Pritchard who, in a series of papers (1892, 1895, 1897), discussed the general sequence from Maude to Geelong and thus established the regional stratigraphic picture in the area. Their work and the results of many other workers in the area, have been synthesized by F. A. Singleton (1941).

The general sequence established by Hall and Pritchard was as follows: At Maude a sequence was exposed consisting of a lower limestone of Janjukian age resting on gravels or Ordovician slate, and underlying a flow of Lower to Mid-Tertiary basalt. Overlying the basalt was a hard pink polyzoal limestone which passed up to a sequence of clays and marls. This entire sequence could be traced down the Moorabool Valley, maintaining a S. dip in excess of the gradient of the stream, so that progressively younger beds passed below the valley floor downstream from Maude.

Hall and Pritchard also noted the SE. dip in the limestone, clays and marls near the Batesford quarry, and concluded that the entire sequence was similarly affected between Maude and Corio Bay. The present work suggests that this trend may not be continuous throughout the area especially between Dog Rocks and the Rowsley Fault where the trend may be absent or even reversed. But poor exposures here do not allow accurate estimates to be made.

The sequence between Geelong and Maude is of particular interest for it was here established conclusively for the first time that the Spring Creek sequence or Janjukian beds were older than Balcombian. Hall and Pritchard recognized the Janjukian age of the Lower Maude Limestone and observed that, at Geelong, the clays, which were clearly higher in the sequence, contained a fauna almost identical with that at Balcombe Bay.

Earlier, McCoy (1874) had adopted the view that the Balcombe Bay sequence was older than that at Torquay and this view was maintained by Chapman and Singleton (1925). Subsequently, Singleton recognized the Balcombian age of the clays at Fyansford and accepted the correlation of Hall and Pritchard. Chapman also, in his later years, modified his earlier views and accepted the Balcombe Bay sequence to be younger than the base of the Torquay sequence.

With this generally accepted correlation, that the Fyansford clays are equivalent to those of Balcombe Bay and that they overlie beds of Janjukian age, Hall and Pritchard successfully resolved a controversy which had plagued early workers in Tertiary stratigraphy.

However, little stratigraphic work was done beyond noting the general position of units in the sequence. Hall and Pritchard recorded several measured sections but made little attempt to describe detailed relationships between formations. Still less attention was paid to the actual lithologies apart from their faunal assemblages.

The present work is an investigation of the detailed stratigraphic relationships of the various formations and a study in some detail of the lithologic facies present in order to reconstruct the conditions under which the sequence was deposited.

Method of Study

Quarter sheets of the Geological Survey of Victoria provide a partial coverage of the area. These include Quarter Sheets 24 SE., 24 NE., and 19 SW. surveyed by Wilkinson, Daintree and Murray. It has been found necessary to modify some geological boundaries and to fill in unmapped areas between these sheets.

However, due to the very flat topography, field studies have been mainly limited to outcrops in the valleys of the Moorabool R. and Sutherland's Cr. which sometimes dissect the area to a depth of 400′ below the level of the plains.

Stratigraphic sections have been measured using a clinometer and checking with an aneroid against local known levels. Representative samples were obtained from the principal sections and submitted to detailed laboratory analysis. Sections measured are presented diagrammatically in Fig. 19; their locations are shown on the geological map, Fig. 1.

Laboratory examination has included size, carbonate and heavy mineral analyses assisted by thin section examination of samples. For accurate carbonate determinations, the Schroetter apparatus has been used; in most cases, however, the percentage soluble in dilute warm HCl approximates the percentage carbonate and has been used to provide a quicker and more convenient method of determination. Samples thus treated are listed in tables under 'percentage soluble', rather than 'percentage carbonate'.

A standard nest of B.S.S. screens (mesh no. 8, 12, 16, 22, 30, 44, 60, 85, 120, 170 and 240) has been used on a Rotap automatic shaking device to carry out size analysis down to, but not including, silt-size. The standard time for screening was 10 minutes.

From the size distributions obtained, cumulative percentage curves and histograms have been constructed from which the following parameters are calculated and recorded in tables:

I. Median diameters (Md)
II. 25% and 75% quartiles (Q_3 and Q_1)
III. Percentiles 10% and 90% (P_{10} and P_{90}).

From these, Trask sorting coefficients ($So = \sqrt{Q_3/Q_1}$) and coefficients of skewness($Sk = Q_3 . Q_1/Md^2$) have been calculated as outlined by Pettijohn (1957).

Locality references in the text refer to co-ordinates on military maps Geelong and Meredith in the 1 Mile series.

Regional Geology

Tertiary sediments were deposited in the shallow shelf seas with shoreline situated N. of Maude. A land area existed to the N. of Maude, consisting of steeply dipping Ordovician sandstones and slates which had been reduced to very low topographic relief following the widespread Mesozoic and early Tertiary planation. In the S. of the area, the tectonically active Mesozoic sandstones of the Barrabool Hills formed a submerged regional high in the early Tertiary sea and eventually were uplifted to form an island in late Tertiary.

Similarly, resistant monadnocks of Palaeozoic granite rising above the general level of peneplained Palaeozoic sediments and now protruding through a cover of Tertiary sediments, formed islands in the Tertiary sea. These include Sutherland's Cr. and Dog Rocks granites. These islands were gradually submerged in mid-Tertiary time. The deepening of the sea responsible for their submergence is thought to have resulted from downwarping of the shelf along the E.-W. margin N. of Maude and possibly associated with other movements, e.g. on the Rowsley Fault.

The oldest fossiliferous Tertiary marine sediments in the area are Janjukian, and are represented by the Lower Maude Limestone. This overlies and passes shorewards laterally into basal sands and gravels which, in turn, are laterally continuous with coarse terrestrial gravels which have accumulated around the margins of the basin near Steiglitz.

The Lower Maude sediments are overlain by basalt, which appears to correspond to a minor regression near shoreline and to a disconformable break in the marine sequence.

At Geelong, this disconformity has not been observed and continuous deposition is thought to have taken place with the accumulation of the basal portions of the Batesford Limestone and equivalent sands, marls and clays.

In early Miocene, or Batesfordian time, slow deepening of the sea occurred with gradual submergence of the granitic island of the Dog Rocks and the transgressive advance of shoreline across the upper surface of the basalt at Maude, eroding it and depositing the Upper Maude Limestone.

The phase of deepest water deposition is represented by the widespread clay facies which overlies the Batesford and Upper Maude Limestones.

The clays pass up to a second disconformity with a phosphatic nodule bed which corresponds to a period of erosion in late Tertiary time before the final deposition of the Pliocene sands and the cessation of marine activity in the area. These latter sands form a very widespread thin sheet over almost the entire area.

Following the retreat of the sea in late Pliocene, little time appears to have elapsed between the initiation of drainage and the extrusion of the early Newer Basalt flows. Throughout the Pleistocene, the area has remained mainly above sea level with non-marine sediments accumulating in places.

Drainage and topographic development during this period has been extensively complicated by successive lava flows over intermittent periods throughout the Pleistocene. These flows cover most of the Tertiary sediments and form the principal plains of the region.

The regional stratigraphy is illustrated in Fig. 2. More detailed relationships compiled from information in measured sections are illustrated in Fig. 3, 19.

Definition and Description of Rock Units

In accordance with stratigraphic procedure, it is proposed to subdivide the sequence into the following rock units, retaining where possible any convenient names used by earlier workers:

- Moorabool Viaduct Sands
- Fyansford Clay
- Batesford Limestone
- Upper Maude Limestone
- Maude Basalt
- Lower Maude Formation—
  - Lower Maude Limestone Member
  - Lower Maude Sand and Gravel Member
  - Sutherland's Creek Sands Member

LOWER MAUDE FORMATION

The Lower Maude Formation is defined as all Lower Tertiary sediments which lie between the Maude Basalt and basement Ordovician slates. It is best seen near the base of section 15 on the E. side of the Moorabool valley at the Maude school.

The formation comprises three members which may be distinguished from each other by distinct lithological differences, yet which are sufficiently related in their arenaceous composition to warrant inclusion as a single formation rather than elevate the formation to the status of 'group'.

In the section at Maude school, 18′ of white sands and gravels rest on Ordovician slates and pass upwards into well-sorted, iron-stained, medium to fine-grained sands. These comprise the lower member, the Lower Maude Sands and Gravels. They are overlain by consolidated calcareous sands or arenaceous limestone defined here as the Lower Maude Limestone.

Both the above members grade laterally eastwards into well-sorted medium-grained sands and quartzite which outcrop in the valley of Sutherland's Cr. and which are defined here as the Sutherland's Creek Sands. These are lithologically distinct from the two former members in that grain size and sorting characteristics are diagnostic. In the valley of Sutherland's Cr., the Lower Maude Sands and Gravels are represented by a thin basal layer of quartzite conglomerate but the Lower Maude Limestone is absent.

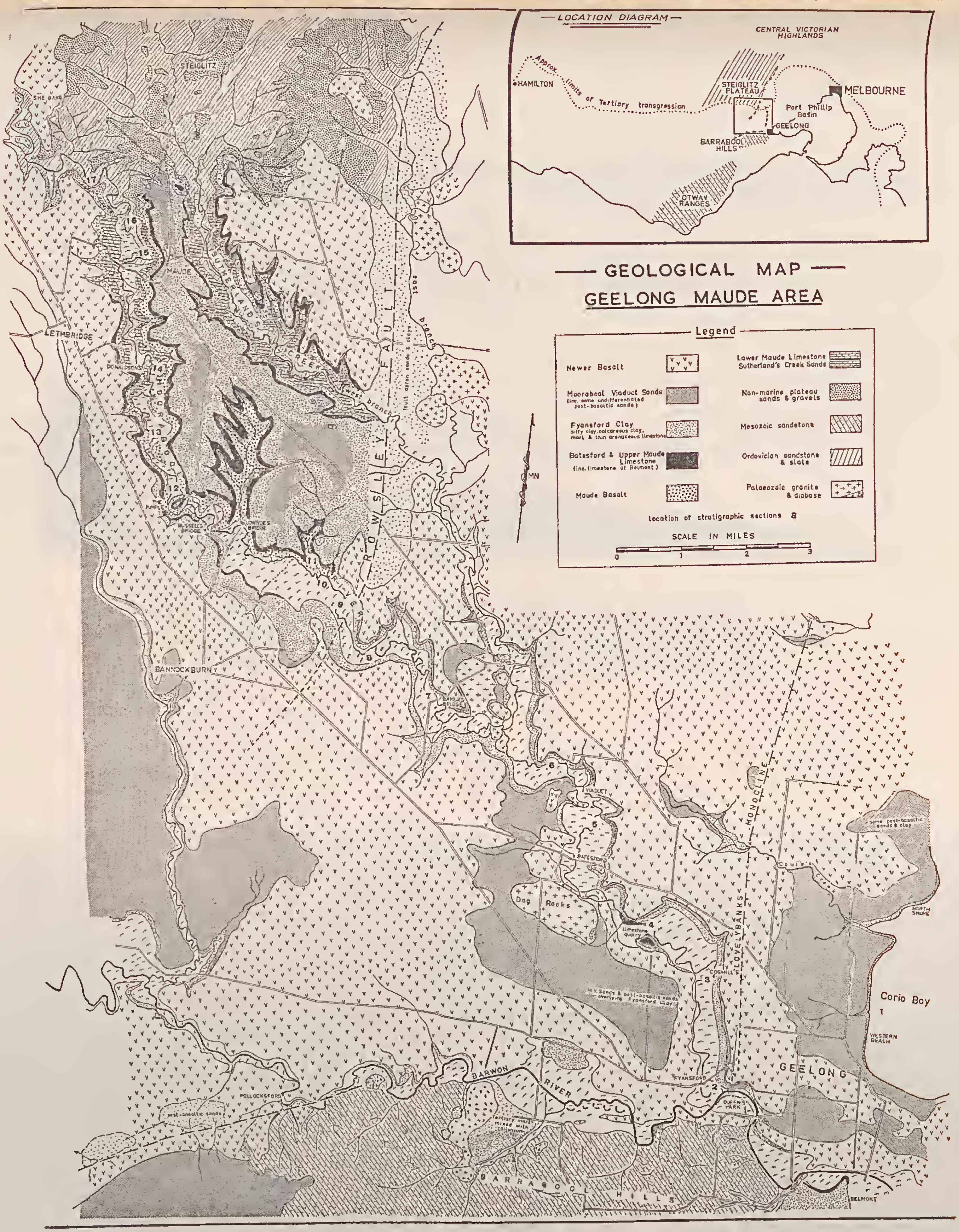


Fig. 1—Geological map of Geelong—Maude area.

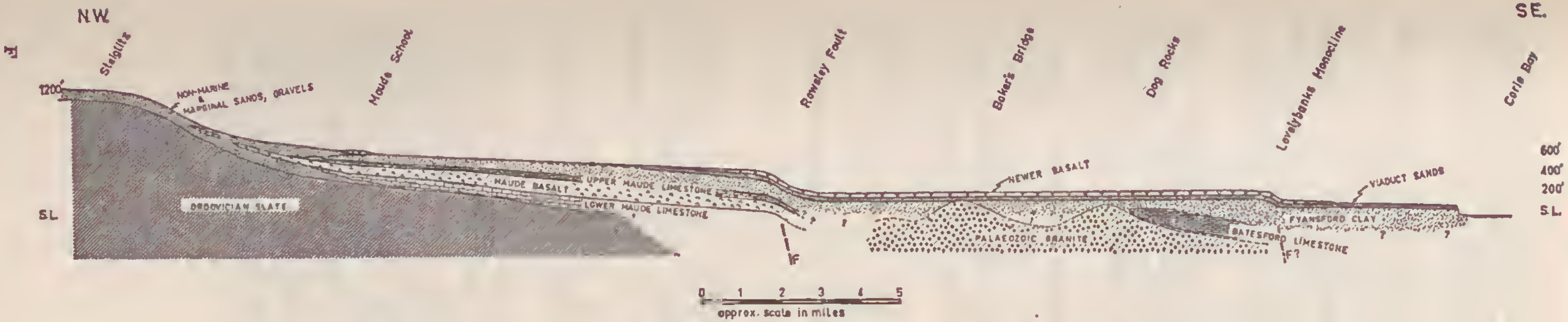


Fig. 2—Regional geological cross-section along the Moorabool R. from Steiglitz to Corio Bay, showing the Tertiary sequence lensing out against Palaeozoic granite and slate.

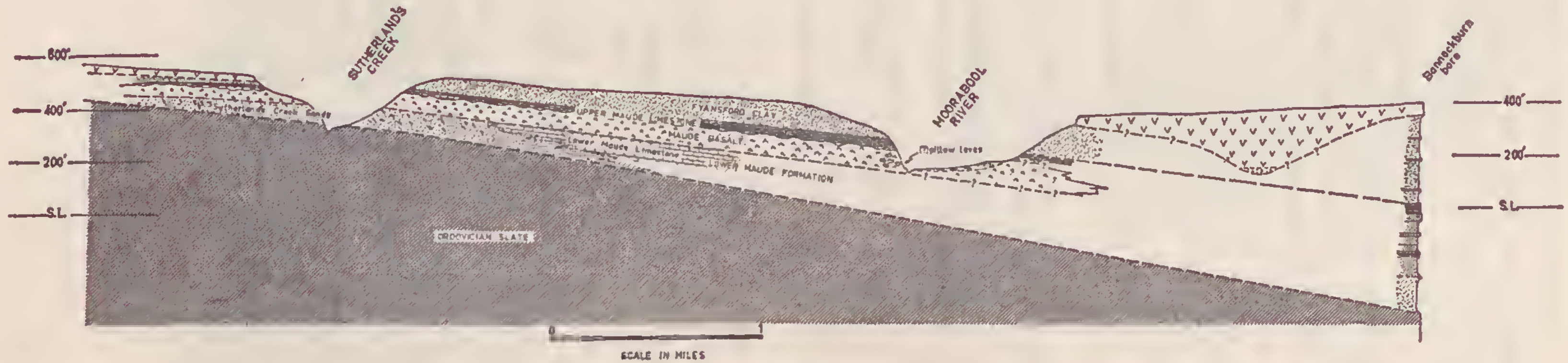


Fig. 3—N.-S. geological cross-section from Mines Department bore at Bannockburn through Russell's Bridge to Sutherland's Cr. showing a lateral facies variation from Sutherland's Creek Sands to Lower Maude Limestone. Note the regional dip to the S. which is due in part to uplift of the N. area. Tertiary marine limestone and clays lens out on rising Ordovician basement a short distance N. of Sutherland's Cr. Legend as in Fig. 19.

LOWER MAUDE SANDS AND GRAVELS

These separate the calcareous and fossiliferous Tertiary sediments from Ordovician bedrock. They are well exposed in the section below Maude school (section 15) and on the S. bank of the Moorabool R. 3 m. NW. of Maude near She Oaks (section 17).

In the former case, 30′ of unfossiliferous sands and gravels grade upwards into calcareous sands and limestone. The gravels increase in thickness to the N. and at section 17, 70′ of sands and gravels underlie the Lower Maude Limestone. Here, a very coarse basal conglomerate in the lower 10′ to 15′ passes up to coarse sands and gravels becoming finer towards the top, and eventually grading into Lower Maude fossiliferous limestone. Some white structureless secondary carbonate is present as matrix in the gravels being derived by precipitation from waters percolating downwards through the overlying limestones.

In lateral extent, the gravels are stratigraphically equivalent to thick non-marine gravels S. of Steiglitz which lie outside the limits of Tertiary marine sedimentation. S. of Steiglitz (½ m. N. of section 17) they reach a maximum thickness of at least 150′ and sometimes underlie outliers of Maude Basalt on the Steiglitz Plateau.

To the S., they lens out rapidly and marine arenaceous limestone rests directly on bedrock at Donaldson's (section 14) 3 m. downstream from Maude (Pl. XV, fig. 2).

To the E., the sands and gravels become finer and are stratigraphically equivalent to the Sutherland's Creek sands and quartzites which are here regarded as marine deposits.

The Lower Maude Sands and Gravels are then a wedge of the more widespread non-marine sediments at the base of the marine sequence, deposited before the Lower Tertiary transgression.

The mineralogy and sedimentary petrology of the sands has not been studied in detail.

LOWER MAUDE LIMESTONE

This member forms the upper portion of the Lower Maude Formation and can be traced from a point about 1 m. N. of Maude school, downstream in the Moorabool Valley, to 2½ m. SE. of Lethbridge where it disappears below river level.

The limestone is poorly exposed being mainly obscured by alluvium or hillwash on the valley slopes.

It has been measured in stratigraphical sections No. 13-16 (Fig. 19).

Sampling has been carried out laterally and vertically to determine significant variations in lithology.

In the type section at Maude school, where the limestone has been studied by Hall and Pritchard and others, it reaches a thickness of 30′ and is overlain by basalt. The limestone grades upwards from non-calcareous sands of the Lower Maude Sands and Gravels into calcareous sandstone and arenaceous limestone. Bedding is well developed and almost horizontal. Individual beds may vary in thickness from ½″ to 1′ or more, although even in the thickest some stratification is usually visible.

Cross-bedding is often evident as at the base of the section at Donaldson's. Here, strongly cross-bedded polyzoal limestone rests directly on Ordovician slate with a high angular unconformity (Pl. XV, fig. 2). Bedding planes are often marked by horizontal animal trails. The sands and gravels which separate the limestone from the slate near Maude, and are absent at Donaldson's, have presumably been eroded by the Lower Tertiary sea.

Although bedding is almost horizontal, the formation maintains a regional dip to the S. At Maude, the top of the limestone is at an elevation of 398 ft, while 3½ m. downstream, where it disappears below river level, it is at an elevation of 190 ft. This represents a gradient of 1 in 90 and is thought to be due in part to initial dip of sediment wedging out against a rising shoreline of Ordovician slates, and in part to slight tectonic movement associated with later uplift to the N.

The limestone is rich in skeletal material but relatively poor in its content of well preserved fossils. Hall and Pritchard (1895) record lists obtained from here but only in several localities are well preserved shells available. At the Maude school section, some bands are rich in fragmental remains of polyzoa, echinoid tests and spines, oyster fragments and various other lamellibranchs. The small echinoid *Fibularia* occurs here in abundance.

The beds are usually friable or mildly indurated except for the zone towards the top where the limestone comes into contact with the base of the Maude Basalt. Here strong ferruginization occurs and samples from this zone do not react with cold HCl, indicating that the carbonate has been replaced by ferric iron, probably derived from the basalt. Partial iron staining occurs throughout the formation, often imparting a reddish brown colour to the rock.

Summary of Petrology and Mineralogy: The limestone is very impure and in places grades into a calcareous sandstone, as indicated by the insoluble residue percentages listed in Table 1. For the samples examined, the average percentage soluble in dilute HCl was 51·2, the range being from 32 in sample No. 5/16·5 from the most southerly outcrop, to 68 for No. 2/17·5C from the base of section No. 14 at Donaldson's.

Table 1

Approximate carbonate : sand : silt-clay ratios from the Lower Maude Limestone

Graph No. on Fig. 4, 5	Sample No.	% Soluble	:	% Sand	:	% Silt-Clay
1	5/16·5	32	:	66	:	2
2	2/17·5 C	68	:	29	:	3
3	629	51	:	47	:	2
4	631	40	:	57	:	3
5	632	64	:	33	:	3
6	633	50	:	47	:	3
7	634	55	:	40	:	5
	Average	51	:	46	:	3

The principal constituents of the limestone are calcite, quartz and clay.

Calcite appears predominantly in two forms, skeletal material and matrix. Partial recrystallization has commenced in some places and it is not always possible to determine whether carbonate was originally matrix or skeletal fragments. However, the latter are always abundant and consist of comminuted fragments of polyzoa, echinoids, lamellibranchs, foraminifera and fragments of the calcareous algae *Lithothamnion*. Very vigorous conditions are indicated by the finely comminuted shelly material which in some samples (e.g. 2/17·5B) is never larger than 0·4 mm. Skeletal fragments often show evidence of algal borings now picked out by iron staining.

Matrix occurs in variable amounts. In samples which are very well sorted, fine-grained matrix is almost entirely absent, as in 18/19·5. In other samples it occurs as interstitial material clouded by clay, and sometimes shows signs of partial recrystallization when it develops into clear granules of calcite.

A third type of carbonate sometimes occurs associated with clay in pellets, as in 2/17·5 A and B. These pellets may occur in the partly recrystallized matrix and are almost indistinguishable from it. They then appear as rounded, cloudy areas with a clear rim of recrystallized calcite. They are approximately the same size as the quartz grains with which they are associated, indicating they have been derived and subjected to the same sorting processes as the quartz. They may represent reworked marl pellets from other areas in the basin, or recrystallized faecal pellets.

Traces of chalcedonic quartz, plagioclase and muscovite occur with a reddish brown or greenish chloritic material showing low birefringence and iron-staining, which may represent altered glauconite. It sometimes occurs infilling foraminiferal and polyzoal chambers or as discrete pellets.

Clay occurs as a minor constituent associated with the matrix. Its absence in most cases is further evidence of effective washing of the sediment during deposition.

Since the skeletal fragments themselves are abraded and have been extensively sorted before deposition with a consistently high percentage of quartz sands, the predominant lithology may be described as a quartzose or arenaceous calcarenite. The arenaceous nature of this member is consistent with its relationships to the Lower Maude Sands and Gravels and the Sutherland's Creek Sands which it overlies and grades laterally into respectively.

Insoluble Residues: These consist almost entirely of quartz, traces of felspar, very little clay and a small percentage of heavy minerals. The quartz grains generally range into the fine to very fine grades on the Wentworth scale, and show a variety of abrasion features. Grains in the fine range are angular to sub-rounded. But in all samples there is a small percentage of medium-grained quartz to 0·3 mm and these invariably bear surfaces which are very well rounded and highly polished.

Size Analyses of Insoluble Residues: Samples of limestone were treated in dilute HCl and residues obtained were sized on screens as described previously. Cumulative percentage curves (Fig. 4) and histograms (Fig. 5) have been constructed from which relevant parameters have been calculated and are listed in Table 2.

Median diameters in all cases are in the range of fine to very fine sand, being considerably finer than the sands to the E. on Sutherland's Cr.

But the most remarkable features of these figures are the values for sorting coefficients (So). A figure of 1·05 for sample 629 is unusual, especially for a water laid deposit. Martens (1939) records a minimum sorting coefficient for 145 beach samples as 1·10 with averages ranging from 1·29 to 1·41. The average recorded here of 1·22 for 7 samples, is better than any recorded by Martens on modern beaches in America. Emery (1960, p. 209) records an average of 1·25 for the inshore sediments at present occurring around Santa Barbara Island.

The quartzose material in the Lower Maude Limestone was probably derived from the abundant sands and gravels occurring on the peneplained Ordovician surface to the N. Poorly sorted equivalents of the terrestrial gravels form the sediment underlying the limestone. Higher in the section, sorting efficiency gradually increases, reaching the maximum in the sample from 4′ below the base of the Maude Basalt (629). Besides indicating vigorous and continuous reworking, this suggests

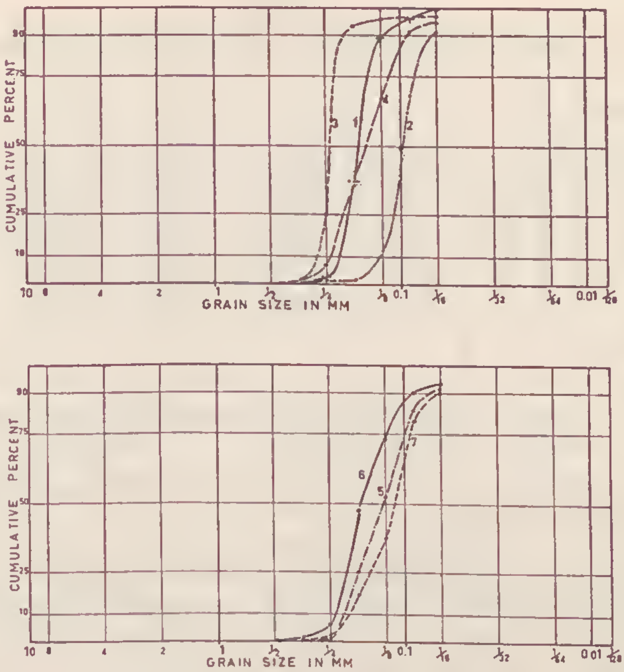


Fig. 4—Cumulative percentage curves of the size distribution of insoluble residues from the Lower Maude Limestone. Graph numbers refer to samples listed in Table 2. For location of samples see Fig. 19.

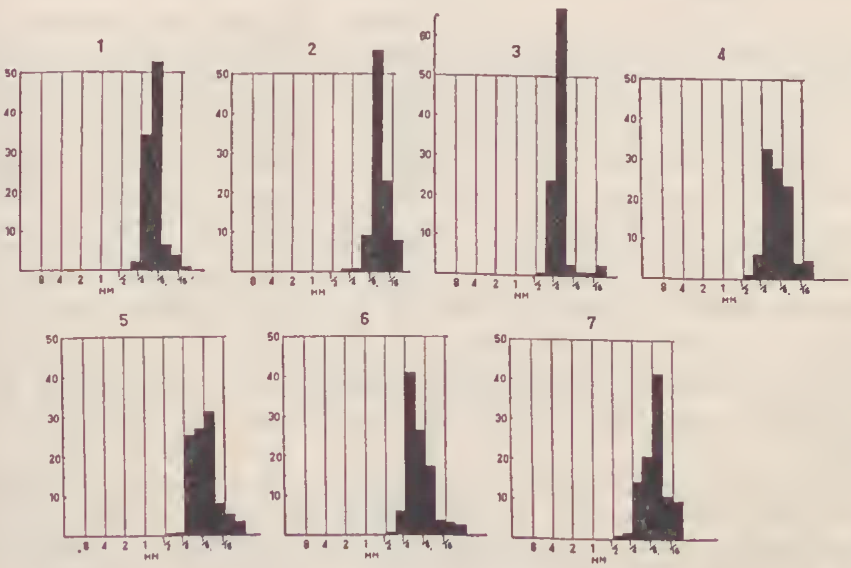


Fig. 5—Histograms showing the percentage distribution of grain sizes in insoluble residues from the Lower Maude Limestone. Sample numbers as in Table 2.

TABLE 2

Sizing parameters from insoluble residues of Lower Maude Limestone

Graph No. on Figs. 4–5	Sample	Md	Q_3	Q_1	P_{10}	P_{90}	So	Sk
1	5/16·5	0·170	0·190	0·145	0·215	0·125	1·14	0·95
2	2/17·5c	0·095	0·110	0·085	0·120	0·068	1·13	1·03
3	629	0·240	0·250	0·225	0·280	0·020	1·05	0·97
4	631	0·155	0·205	0·115	0·240	0·092	1·33	0·98
5	632	0·130	0·180	0·100	0·210	0·072	1·34	1·06
6	633	0·170	0·210	0·120	0·230	0·088	1·32	0·87
7	634	0·110	0·150	0·094	0·200	0·065	1·26	1·16
	Average	0·153					1·225	1·003

Positions of samples in the sequence has been recorded where possible on the relevant stratigraphic sections (Fig. 19).

that there was very little new material being supplied to the environment at the top of the Lower Maude Limestone.

SKEWNESS (SK) : The values calculated from 7 samples from the Lower Maude Limestone (Table 2) indicate positive skewness for 3 samples, and negative for 4, with an average half-way between, indicating a very uniform distribution about the median diameter.

Martens (op. cit.) and more recently Friedman (1961) have recorded positive Sk values in almost all cases analysed from beach samples. Pettijohn (1957) notes that off-shore silts tend to have negative skewness. The values recorded here occur between these, consistent with deposition in an in-shore shallow marine environment, but not a beach zone.

HEAVY MINERAL ASSEMBLAGE: The mature assemblage recorded in Table 3 indicates a source area of the strongly weathered sedimentary rocks. The detrital mineral fraction of the limestone has apparently been derived mainly from the weathered Palaeozoic sandstones, shales and slates which outcrop nearby. The abundance of well rounded zircons and tourmalines suggests that the assemblage may have passed through several cycles of deposition. However, a small percentage of euhedral zircons suggests that at least some sediment was being eroded from granites nearby, some of which now outcrop a short distance to the E.

Zircons show better rounding with increased height in the section. This supports the idea that while detrital material was being vigorously reworked in a near-shore marine environment, very little fresh detritus was being supplied to the basin which would have maintained the percentage of euhedral zircon.

Moreover, this tendency towards better rounding towards the top of the limestone is associated also with better sorting coefficients (So) in this zone (1·05, 1·26 for samples near top; 1·33, 1·34, 1·32 for samples near the base of the limestone member).

ENVIRONMENT OF DEPOSITION: The presence of prominent cross-bedding, and very well sorted, fine sand-size detrital material mixed with abraded skeletal carbonate, all indicate deposition in a shallow in-shore zone along the margins of the basin to which little detritus was being supplied. A low mature topography must already have been developed on the land area to the N. with lateral erosion dominant rather than vertical stream incision. In the sub-tropical climate which existed in

TABLE 3

Heavy mineral assemblage of Lower Maude Limestone

Sample No.	Zircon	Tourmaline	Rutile	Leucoxene	Muscovite	Chlorite	Garnet	Andalusite	Epidote	Corundum	Apatite	Topaz	Amphibole	Brookite	Opaques
5/16·5	a	a	r	r	r	V	V				r		V		c
2/17·5c	A	c	V	r						V					c
629	A	c	r	r	r			V							c
631	A	c	o	r	o	r	V		V		V	V			c
632	A	c	r	r	V	V		V						V	c
633	A	c	o	o	o	r			V				r		c
634	A	c	r	o	r	r							V		c

A...very abundant o...occasional
a...abundant r...rare
c...common V...very rare
(Similar notation is used in all tables of heavy mineral asseblages.)

Victoria during Lower and Mid-Tertiary time (indicated by lignites, laterites and important warm water faunas) such topography would develop a deeply weathered profile and contribute very mature sediments to the adjacent basin.

SUTHERLAND'S CREEK SANDS

This member is defined as the well-sorted and pure quartz sands or orthoquartzites often extensively cemented by secondary silica, and typically seen at locality 270,160 in the valley of Sutherland's Cr.

They outcrop at intervals along the entire length of Sutherland's Cr. from N. of Maude school to the Rowsley fault scarp in the E. Stratigraphically, they occur between the Maude Basalt and Ordovician slates in the same relative position as the Lower Maude Limestone. Poor exposures prevent accurate determination of thicknesses, but the sands are thought to reach nearly 100′ near locality 270,160 half-way between the school and the fault scarp. They wedge out to the N. until Maude Basalt eventually rests on Ordovician slate with only a thin layer of sands, gravels or siliceous conglomerate between.

The sands are often loose and unconsolidated but there is a prominent development of dense quartzite at intervals all along the valley of Sutherland's Cr. The resistant quartzites stand out on the valley slopes forming a prominent and easily recognizable feature of the sequence.

Near horizontal bedding is apparent in outcrops of both sands and quartzites although there is a low regional dip to the S. as in the case of the Lower Maude Limestone. In quartzite bands, bedding is often picked out by secondary silicification resulting in prominent banding. Associated with secondary silica, iron-rich solutions have also permeated the sands to a slight extent accentuating the banding by the formation of reddish zones of iron staining. Unlike the related Lower Maude Limestone, cross-bedding is rarely developed.

In the vicinity of the Rowsley Fault (locality 297, 142), large blocks of friable sandstone outcrop showing well developed shearing and jointing due to tectonic movements on the fault.

MINERALOGY: The sands consist of very pure quartz sands, well sorted and well rounded with a complete absence of calcareous material. Wherever they are only mildly indurated, as near the fault, they are porous and permeable. But in areas affected by secondary silicification, pore space has been effectively filled by secondary overgrowth or by infillings of cryptocrystalline quartz. In most cases (e.g. sample 2/S·1) original quartz grains have been enlarged by overgrowths until interference from neighbouring grains has prevented further growth. Some of the original grains contained large numbers of inclusions so that on secondary addition, a clear rim of quartz overgrowth has formed, leaving the darker centre to mark the shape and size of the original grain, thus allowing an estimate to be made of the amount of secondary enlargement.

The resultant quartzite forms an extremely hard rock which breaks with a sharp edge and has been extensively used by aborigines for making implements, probably scrapers. In many places along Sutherland's Cr. the ground is littered with quartzite fragments. A careful search yielded only a few flakes showing secondary working but no artefacts of any significance.

Quartzite blocks often bear small elongate tubular cavities to 5 mm diameter, penetrating into the body of the rock. The origin of these is not known but they have facilitated the passage of siliceous solutions. In their immediate vicinity, an unusually high proportion of cryptocrystalline and chalcedonic silica occurs surrounding the original grains.

The cause of secondary silicification is almost certainly associated with the extrusion of the overlying Maude Basalt and, in this respect, the quartzite resembles the widespread sub-basaltic quartzites in other parts of Victoria.

SIZE ANALYSES: The results of mechanical analyses are set out in Table 4 and Fig. 6, 7.

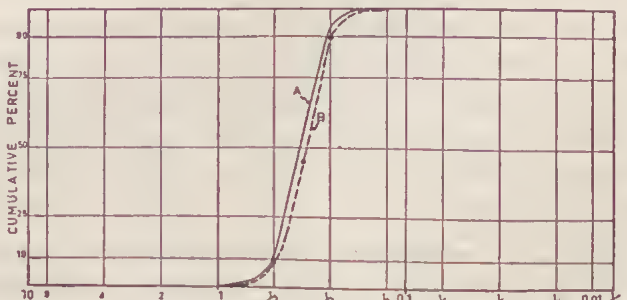


Fig. 6—Cumulative percentage curves showing size distribution of Sutherland's Creek Sands. For parameters see Table 4.

Very good sorting is evident even in the field, and this is confirmed by the sorting coefficients (1·23 and 1·17) which are comparable to the coefficients of the insoluble residues of the Lower Maude Limestone.

ROUNDING: The quartz grains are generally well to very well rounded, with high sphericity and are often highly polished (Pl. XVIII, fig. 4). The polished surfaces may be due to a very thin veneer of secondary silica, but rounding and sphericity indicate intense abrasion before final deposition.

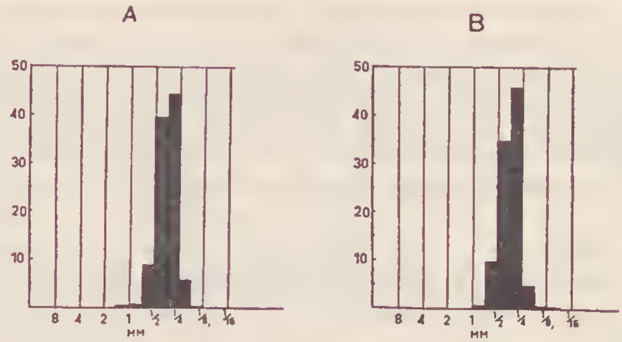


Fig. 7—Histograms showing the percentage distribution of grain sizes in samples from Sutherland's Creek Sands. Samples as in Table 4.

HEAVY MINERALS: The heavy mineral suite generally resembles that of the Lower Maude Limestone in its abundance of stable minerals, zircon, tourmaline and rutile. However, zircons and tourmalines show better rounding than those from the Lower Maude Limestone and there is a much higher percentage of andalusite. This is apparently derived from spotted slates which outcrop in the valley of Sutherland's Cr. adjacent to the Rowsley Fault, and immediately underlie the Sutherland's Creek Sands. The relative absence of this mineral in the Lower Maude Limestone to the W. could be due either to rapid breakdown along cleavage planes in a zone of intense wave energy, or to a predominance of W.-E. currents.

TABLE 4

Sizing parameters for Sutherland's Creek Sands

	Md	Q_3	Q_1	P_{10}	P_{90}	So	Sk
Sample A	0·330	0·415	0·272	0·475	0·240	1·23	1·04
Sample B	0·335	0·400	0·290	0·480	0·250	1·175	1·03

ENVIRONMENT OF DEPOSITION: The increase in rounding of the quartz grains, zircons and tourmalines, suggests even more energetic abrasion than in the environment in which the Lower Maude Limestone was deposited. Moreover, a comparison of the results of mechanical analysis confirms this view. Although the average median diameter is considerably larger than in the case of the Lower Maude Limestone residues (0·332 mm compared to 0·153 mm), the sorting efficiency does not show a corresponding decrease which normally accompanies an increase in grain size (van Andel and Postma 1954, Pettijohn 1957). An average sorting coefficient of 1·20 compares more than favourably with the average for the limestone residues (1·225).

The mechanical action, therefore, was even more vigorous for the deposition of the coarser Sutherland's Creek Sands than for the finer detritus of the Lower Maude Limestone.

Moreover, the positive skewness recorded here (1·04) resembles that recorded by Pettijohn (1957) and confirmed by Friedman (1961) in beach deposits, i.e. a tendency to be skewed towards the coarser fraction.

The evidence suggests that while the Lower Maude Limestone was deposited close to a shore line, the sands of Sutherland's Cr. were a beach deposit. The preservation of beach deposits as ancient sediments are rarely recorded in the literature, due to the facility with which unconsolidated beach sands are eroded either under submarine conditions, by the vigorous wave action of a regressive or transgressive sea, or by subsequent subaerial erosion. However, along Sutherland's Cr. these sands have been preserved intact by the cover of basalt.

TABLE 5

Heavy mineral assemblage of Sutherland's Creek Sands

	Tourmaline	Zircon	Andalusite	Rutile	Leucoxene	Ilmenite	Magnetite	Kyanite	Epidote	Anatase	Topaz
Sample A	A	c	c	c	c	c	c	V			V
Sample B	A	c	c	c	o	o	c		V	V	

A...very abundant
c...common

o...occasional
V...very rare

The complete absence of carbonate, which is so abundant in the lateral equivalents to the west, is attributed to initial conditions of very effective sorting in a zone of high energy which resulted in an effective gradation of grain size from coarse to fine away from shoreline. Any coarse carbonate coming into the high energy beach zone would be rapidly preferentially abraded and deposited with finer material in a near or off-shore zone, but not in the beach zone. Unfortunately, a covered interval hides the lateral continuation of the Sutherland's Creek Sands towards the off-shore zone so that the transition to the Lower Maude Limestone cannot be studied in detail. But from their relative stratigraphic positions there is no alternative but to regard both these members as laterally equivalent.

SUMMARY: The relationship between the Lower Maude Sands and Gravels and the Lower Maude Limestone is one of a vertical transition from a non-marine to marine facies. Near shoreline and the Maude school, portion of the gravels can be seen to underlie the limestone so that the terrigenous sediments must be in part older than the marine. But higher in the sequence, a lateral transition from non-marine to marine facies is also present so that the former may be in part synchronous with the limestone.

Along Sutherland's Cr. the Lower Maude Sands and Gravels are represented by merely a thin silicified basal conglomerate, and rapidly pass upwards to marine Sutherland's Creek Sands.

The variations evident between the laterally equivalent Sutherland's Creek Sands and the Lower Maude Limestone, from shoreline to an off-shore direction, comprise a decrease in grain size, a large increase in carbonate content, and a decrease in the extent of secondary silicification. It is perhaps significant that no secondary silicification occurs in this area whenever carbonate is retained in the sediment.

MAUDE BASALT

A basalt flow separates the Lower Maude Formation from the younger marine Tertiary sediments near Maude. Since it overlies beds of Janjukian age (Hall and Pritchard 1895, Singleton 1941) therefore it is younger than some Older Basalts *sensu stricto* such as that at Airey's Inlet which underlies Janjukian sediments (Raggatt and Crespin 1955).

The basalt reaches a maximum thickness of approximately 100′ near Lethbridge (section 13) where the best exposures are located. Intermittent outcrops occur along the Moorabool Valley from 2 m. N. of Maude to the intersection with the Rowsley Fault, but generally the basalt is obscured by a soil cover of heavy black clay. Small isolated outliers occur N. of Maude capping Ordovician slates and Lower Tertiary non-marine gravels.

The lava maintains a regional gradient to the SE. which carries it below the floor of the Moorabool Valley on the S. of Lownde's Bridge. It does not occur in deep bores at Bannockburn 2 m. S. of Lownde's Bridge. Its distribution indicates that the flow originated from a vent in the N., and flowed in a southerly direction onto calcareous marine sediments at Maude.

The mineralogy has been described by Edwards (1939) and Coulson (1938) as a normal labradorite, olivine, augite basalt.

Vesicles are rarely developed except at the base of the flow. Small horizontal joints or laminae are common and are probably due to layering during flow. When fractured, the rock often breaks along these planes.

In the decomposing basalt, many of the original structures can be picked out by prominent secondary carbonate infillings. In a quarry ½ m. N. of Russell's Bridge, there is evidence of columnar jointing in an exposure 15′ thick. Broad columns can be traced from top to bottom of this quarry and their presence leaves little doubt that the basalt was extruded and crystallized under sub-aerial conditions as far S. as this locality at least.

Half a mile further S., in the road cutting on the N. side of Russell's Bridge, large ovoid structures of harder basalt occur in a soft palagonitic matrix indicative of lava pillows. They are marked by a clear tachylitic rim approximately 2″ thick which passes inwards to decomposed basalt. Pillows occur from 1′ to 3′ diameter, and occasionally can be seen to be packed, one on the other (Pl. XVI, fig. 2). Polygonal fractures traverse the pillows and are infilled with a secondary carbonate. These are the only structures exposed in the area which suggest sub-aqueous cooling of the lava.

The significance of this is important in the reconstruction of the palaeogeography, for regression must have occurred after the deposition of the Lower Maude beds to allow the extrusion and cooling of basalt in such a way as to give normal columnar jointing passing to pillow lavas near Russell's Bridge. The lava pillows at this locality may have originated by basalt flowing into either a marginal marine environment, or fresh-water drainage channels. However, there is little evidence to suggest that any significant drainage was initiated on the surface of the Lower Maude beds before the extrusion of lava. Any drainage would rapidly erode unconsolidated Sutherland's Creek Sands causing scouring and other disconformable features. It is concluded, therefore, that a very small interval of time elapsed between the retreat of the sea from the Maude area and the extrusion of the lava onto the Lower Maude Formation.

In the absence of any signs of fresh-water erosion, there is a strong possibility that the pillows at Russell's Bridge originated by lava flowing into the edge of the sea, so that the new shoreline at this period may have been located near Russell's Bridge, in contrast to its former position N. of Maude school during the deposition of the Lower Maude Formation.

The significance of this local regression is discussed later.

UPPER MAUDE LIMESTONE

This formation is defined as the fossiliferous and calcareous sediment lying directly on Maude Basalt and continuing vertically to top of bed D in section 15 near the Maude school. It has been referred to in earlier literature as 'Upper Maude beds' (Hall and Pritchard 1895) or merely 'upper beds at Maude' (Singleton 1941). It can be traced along the Moorabool R. from the vicinity of the Rowsley fault scarp to a point approximately 1 m. NE. of Maude. The thickest recorded occurrence is 39′ in the type section at Maude school where beds of limestone occur interbedded with silty marls.

Near horizontal bedding is usually evident and in some places, e.g. in quarry on road S. of Maude school the limestone shows well developed cross-bedding. Over the entire length of its occurrence it shows many variations in lithology but one of its most characteristic features is a very dense pink microcrystalline texture with abundant fossil remains. The rock is crowded in some places with moulds and casts of large rocky bottom mollusca, found especially in close proximity to the underlying basalt (Pl. XVI, fig. 1).

An erosion surface at the top of the Maude Basalt forms a disconformity separating the basalt from the limestone. Limestone is often observed infilling large irregularities in the basalt and in some cases is draped over basalt in a supratenuous fold. Wherever the limestone-basalt contact is exposed, well rounded basalt cobbles may be found completely enclosed in the basal portions of the limestone. In section 13, limestone can be seen penetrating down into the basalt. At this locality, a thin horizontal band of limestone several inches thick occurs in the basalt to 14′ down from the surface of the lava. This could be mistaken for two flows of basalt separated by a thin intervening band of limestone. This was probably the outcrop that led the Geological Survey workers, Wilkinson and Murray, to the interpretation shown on the Quarter Sheet No. 19 SW., where a thin limestone band is shown intercalated between basalt flows. It was pointed out by later workers (Hall and Pritchard 1895, Singleton 1941) that the probable explanation lay in the irregular nature of the limestone-basalt contact. Evidence cannot be found to confirm the interpretation of Wilkinson and Murray. The horizontal band of limestone here has originated by percolating into an eroded crevasse. Associated with it is an occurrence of limestone filling amygdaloidal hollows to 6″ diameter and in some other places it can be seen percolating into the basalt along vertical joint planes.

The relationship to the basalt is interpreted, therefore, as a disconformable one, with erosion taking place in an advancing sea, followed by deposition of limestone under shallow conditions on the basaltic sea floor, which supported a particularly strong, well developed, benthonic molluscan fauna.

Lithology and Mineralogy: The dense pink microcrystalline limestone is limited to the basal part of the formation and rapidly passes up to bedded sandy limestone, as in a quarry exposure E. of Lownde's Bridge, where bedded sandy limestone is overlain by 8′-12′ of sandy clays with prominent ferruginous pellets. Quartz sands associated with the limestone are often coarse, rounded and highly polished. In another quarry S. of the Maude school, well sorted, abraded polyzoal limestone occurs with prominent cross-bedding and a considerable percentage of rounded and well sorted quartz. In the most northerly exposures closer to the shoreline (section 15 and 16) the beds become very arenaceous.

The lithology then is very variable, but generally a relatively high percentage carbonate occurs in proximity to the basalt, rapidly increasing in insoluble detritus with increasing height in the section.

In the detailed study of this formation, attention has been concentrated on the carbonate-rich bands in an endeavour to ascertain the origin of the carbonate fraction. The analyses therefore are somewhat biased in favour of these beds and percentage carbonate averages thus obtained are not representative of the formation as a whole.

The percentage soluble in acid (approximately equal to percentage carbonate) has been determined for 8 samples from various outcrops (Table 6). These samples indicate an increase in the percentage insoluble detritus with proximity to shoreline. Samples which show the highest proportions of insoluble residues (3/19·6 and 14/19·6D) were from the most northerly outcrop.

Nevertheless, the average percentage (80·6) for these lime-rich bands represents an overall low content of detrital material.

Carbonate: The carbonate present is usually in the form of relatively coarse skeletal material often associated with very fine-grained microcrystalline matrix. Well sorted skeletal material devoid of matrix sometimes occurs as in the quarry S. of Maude school.

Table 6

Percentage ratio of carbonate : sand : silt-clay from Upper Maude Limestone

Sample No.	% Soluble	:	% Sand	:	% Silt-Clay
6/16·5	84·7	:	11·5	:	3·8
10/16·5	89·7	:	5·5	:	4·8
4/17·5	85·0	:	6·3	:	8·7
1/19	73·2	:	21·8	:	5·0
13/19·6	66·1	:	30·4	:	3·5
14/19·6 A	89·1	:	10·0	:	0·9
14/19·6 D	51·2	:	46·2	:	2·6
*628	87·4	:	4·6	:	8·0

* Sample containing *Lepidocyclina* from section at Maude school.

The skeletal material present consists principally, in approximate order of abundance, of fragments of *Lithothamnion*, polyzoa, large and small mollusca, foraminifera, and echinoid plates and spines. *Lithothamnion* fragments occur in abundance, ranging from coarse fragments to 1 cm or more, found in the basal part of the limestone, to scores of minute subopaque skeletal pellets from samples near the top of the formation. *Lithothamnion* coralline algae are known to thrive on rocky shorelines in the zone of intense wave action. At Bikini and other Pacific atolls, they form fringe reefs in the shallow intertidal zone in the areas of greatest wave energy (Tracey, Ladd and Hoffmeister 1948; Wells 1957). They form an extremely resistant feature on the littoral zones of some tropical to sub-tropical shorelines. The deposition of portion of the Upper Maude Limestone probably occurred on such a rocky littoral zone subject to intense wave action. Furthermore, the oxidized nature of the sediment and some occurrences of intraformational corrosion further indicate very shallow water conditions.

After the deposition of the lower part of the formation, bottom conditions changed. The rocky basaltic sea floor was covered by abraded sandy skeletal carbonate. Coralline algae and the rocky bottom benthonic molluscan fauna gave way to a more normal sandy bottom fauna. A vertical study through the formation shows a change in the abundance and grain size of *Lithothamnion* fragments with increasing height in the section. Algal fragments persisted for a long time as abraded and resorted material, eventually being redeposited in the later sediment as small calcarous sub-opaque and well rounded pellets often almost devoid of organic structure.

Pellets and skeletal material often show the effect of algal borings (e.g. sample No. 10/16·5). Minute brown burrows appear as a network in abraded fragments, often with a red-brown limonitic infilling which picks out the algal traces. Suspected faecal pellets also affected by algal borings have been observed.

MATRIX: Pore space interstitial to skeletal fragments is often infilled with very fine-grained microcrystalline matrix. In some samples, matrix constitutes the greater proportion of the rock. In one sample (1/16·5) which was located from a vugh in the basalt, the rock consists entirely of microcrystalline matrix free of skeletal material. From the same locality an interesting specimen occurs (No. 10/16·5) which was located in a crevasse in the basalt.

In this sample, typical skeletal remains are present as coarse to fine, poorly sorted material lying parallel to bedding. The rock has a very dense pink crystalline appearance which is due to almost complete infilling of pore space with calcitic matrix. Grain size is barely resolvable under high power. The matrix is associated with fine quartz grains (to approx. 0·1 mm) and a considerable proportion of reddish brown clay which results in a clouded pink and semi-opaque appearance. In addition to skeletal material and matrix, a third form of carbonate occurs as cement. This is clear sparry calcite which occurs as infillings in some of the fossil cavities. In 10/16·5 such cavities occur with their basal portions half filled with clouded microcrystalline material identical to the matrix surrounding the fragments. In the upper part of the cavities, either filling them or nearly doing so, are larger crystals of clear irregular calcite representing cement introduced after deposition (Pl. XVIII, fig. 1).

The association of calcite matrix with clay both inside and outside the fossil cavities is thought to be due to lime mud chemically or organically precipitated as aragonite but now converted to calcite. In the sample in question, protection in a basalt crevasse, has resulted in very poor sorting so that the mud could readily accumulate with coarse skeletal fragments.

In the same sample, minute graded bedding is apparent. Distinct bedding planes can be traced across the thin section, often truncating fossil remains, even the resistant *Lithothamnion.* This indicates that skeletal fragments rapidly became cemented in the lime mud which was infilling the crevasse. Later solution, perhaps in a shallow intertidal zone where intermittent flooding and evacuation would occur, began to attack and dissolve the deposited material resulting in the small-scale scours. Approaching a scoured surface, matrix becomes pinker, indicating an oxidized horizon. The horizon itself is pencil sharp above which there is a sudden increase in the grain size of quartz and skeletal material and an associated colour change to a less ferric appearance. The cycle is then repeated as the sediment grades up once more to a ferric-red clay matrix and another minute scour overlain by coarser material. The scour associated with iron-stained bands and cyclic change in grain size indicates successive stages of infilling and oxidation. The scale involved is in the order of several centimetres.

A similar effect on a larger scale has been observed in a bed 1′ thick in the quarry E. of Lownde's Bridge. The lower portion of the bed is well sorted, porous skeletal limestone. The top of the bed is marked by an increase in matrix resulting in a gradation from a porous to dense limestone. The upper surface appears abraded or partly redissolved with fossils truncated. This is then overlain by another bed of porous polyzoal limestone. Bedding appears to represent an hiatus with carbonate mud percolating down into porous skeletal limestone filling pore space and giving a dense appearance to the upper portion of the bed. During this hiatus, partial solution or abrasion occurred before the deposition of the next bed.

The evidence of truncated *Lithothamnion* fragments on these horizons indicates that lithification had already commenced so that individual skeletal fragments were already cemented before corrosion took place. Carbonate diagenesis is not generally known to occur whilst the sediment is still beneath the sea (Ginsburg 1957) but is a common feature of intertidal areas where wetting and drying are associated with solution and precipitation of carbonate, often resulting in the characteristic feature known in recent sediments as 'beach rock'.

It is probable that similar intertidal conditions affected some parts of the Upper Maude Limestone allowing diagenesis to occur followed by intermittent periods of corrosion or corrasion.

ORIGIN OF LIMONITIC PELLETS: In the quarry ½ m. E. of Lownde's Bridge a bed of yellow-brown calcareous clay occurs, 4′ to 10′ thick, overlying pink polyzoal limestone. This clay horizon contains a profusion of dark brown highly polished limonitic pellets. Limonitic material has replaced fragments of polyzoa, echinoids, lamellibranchs and foraminifera. Occasional sharks' teeth also have been found. Pellets are usually well rounded and vary greatly in size from shell fragments ½″ in diameter to minute replaced foraminifera. These are mixed evenly through a bed of fine calcareous clay, making in all a very poorly sorted bed.

When the pellets are heated in dilute HCl the limonite is dissolved out leaving a residual mould of clay-like material, very finely divided and with low birefringence. The refractive index of this residue is 1·588 which approximates to some of the chlorites, particularly chlinochlore or nontronite.

The origin of this material is uncertain. It has a similar appearance to oxidized glauconite, but there is no sign of unoxidized glauconite associated with it. There is little doubt that the pellets originated in a zone of strong oxidation. Similar pellets occur throughout the limestone mixed in with the skeletal fragments but rarely in the concentration in which they occur in the quarry above. Moreover, they always occur in the red-brown oxidized state, even when found in fresh dense limestone, indicating that oxidation had occurred before final deposition. Such oxidation could not occur under submarine conditions.

It is concluded therefore that these pellets are *remanié* in origin and represent material, perhaps originally glauconitic, which was exposed to sub-aerial weathering and later reworked and deposited in the Upper Maude Limestone.

Regression which preceded the extrusion of the Maude Basalt would have exposed marine sediments of the Lower Maude Formation to sub-aerial weathering. Much of these were quickly covered and protected by the lava flow, but some marine sediments outside the limits of the flow undoubtedly remained exposed to weathering. These may have contributed the *remanié* oxidized pellets to the Upper Maude Limestone although diagnostic fossils have not been found.

Dolomitization: Samples of the limestone have been tested for dolomite using the techniques outlined by Friedman (1959) and later confirmed by Wolf and Warne (1960).

The greater percentage of the carbonate present is calcite but all samples of the dense pink limestone showed signs of at least small amounts of dolomitic carbonate. Using titan yellow in NaOH, dolomite shows as a pinkish to bright red stain varying in intensity with the degree of dolomitization. One sample (1/16·5) from within an amygdale near the top of the Maude Basalt proved to be almost pure dolomite. The sample did not react with cold dilute HCl and stained to a uniform bright red in titan yellow. In thin section, skeletal material is completely lacking, the rock consisting of very fine-grained microcrystalline carbonate which can barely be resolved under high power magnification.

The origin of this specimen is uncertain. Assar Hadding (1958) has postulated a biochemical origin for limestones of similar texture. The absence of any clear sparry crystals suggests an origin other than chemical precipitation from secondary carbonate solutions; and the similar absence of any skeletal material whatsoever indicates that it was not due to the downward percolation of lime mud from the sea floor, which is usually thoroughly mixed with organic shell fragments. However it originated, ample magnesium was available from the extensive decomposition of the olivine in the basalt, and there is little doubt that the dolomite has originated in this manner. In the samples less closely associated with the basalt, the intensity of dolomitization decreases markedly. It can be classified into three modes of association:

(i) Skeletal fragments of originally high magnesium content are picked out by the pink stain. This applies especially to some foraminiferal tests and some *Lithothamnion* fragments. A similar feature was noted by Wolf and Warne (1960) in application of staining techniques to modern organisms.

(ii) Matrix often shows signs of dolomitization when associated with the infilling of polyzoal chambers.

(iii) Weathering surfaces and drusy linings show positive stains for dolomite and discrete dolomite rhombohedra are sometimes visible on etched surfaces.

The latter two methods of occurrence are due to secondary enrichment of the lime matrix by magnesium available in solution from the decomposing basalt.

The pink colour of some parts of the limestone cannot be attributed to dolomitization since many such samples show only very faint traces of dolomite. It may be due to oxidation shortly after deposition, or perhaps to the presence of organic dyes retained in the sediment in such an algal environment, although *Lithothamnion* fragments bleach rapidly in modern sediments after fragmentation (Tracey, Ladd and Hoffmeister 1948).

Insoluble Residues: Both heavy and light fractions indicate that the weathering of granites contributed detritus to the sediment at the time of deposition of the limestone. This is suggested by the persistent occurrence of coarse biotite and a small but important percentage of euhedral zircons.

Quartz is consistently present in some bands through the limestone, commonly occurring as very well rounded and polished grains to approximately 2 mm diameter. These suggest a long period of abrasion and perhaps several cycles of deposition.

Augite occurs in the heavy fraction from most samples, being derived from the erosion of underlying basalt. The source of persistent hornblende (see Table 7) is not known. No rocks containing fresh hornblende now outcrop in the area, the nearest being the epidiorite on the Dog Rocks granite some 10 m. to the SE.

Another characteristic mineral of the assemblage resembles aggregates of small zircons, sometimes appearing as a large rounded grain with a frosted 'potato' shape, and sometimes with an apparent clay skin. The precise nature and source of this mineral are not known and it is tentatively included in Table 7 as mineral 'A'.

Table 7

Heavy mineral assemblage from Upper Maude Limestone

Sample No.	Zircon	Tourmaline	Rutile	Hornblende	Augite	Chlorite	Biotite Muscovite	Andalusite	Topaz	Garnet	Epidote	Anatase	Magnetite	Leucoxene	Mineral 'A'
6/16·5	c	o	r	o	r	o	o			V	V		o	o	r
10/16·5	c	c	r	o	r	o	r					V	o	o	r
4/17·5	a	c	o	c	c	c	o	V	r	V		V	o	o	o
1/19	c	o	r	r	o	o	r						r	o	
13/19·6	c	o	r	r	r	c				V			r	r	r
14/19·6A	a	c	o	o	V	c	r	V	V				o	o	r
14/19·6D	c	o	r	r		c	r			V			r	r	r
628	c	c	r	o	r	c	r						o	r	o

a...abundant
c...common
o...occasional
r...rare
V...very rare

Secondary manganese occurs near the base of the formation at Maude (bed 'A' in sections 15 and 16). Small clots of soft black opaque and sometimes dendritic mineral have developed in the pore space imparting a speckled appearance to the bed.

Age of Upper Maude Limestone: A fauna of Batesfordian age occurs in limestone immediately overlying basalt near the Maude school. *Lepidocyclina* is here associated with *Gypsina howchini* in limestone containing rounded cobbles of basalt (sample 628). This enables the limestone from the northern region to be correlated with the upper part of the limestone in the Batesford quarry, the type section of the Batesfordian.

Environment of Deposition: The Upper Maude Limestone was deposited in the shallow waters of an advancing sea on a rocky sea floor of eroded Maude Basalt. A fauna of large benthonic mollusca and resistant coralline algae thrived in the shallow agitated and aerated waters of this environment.

Carbonate deposition occurred principally in the form of lime mud and well sorted skeletal carbonate sands. This resulted in changes in the sea floor environment which led to extensive changes in the faunas. Large crawling mollusca gave way to sandy bottom forms. Littoral coralline algae were either drowned in the deepening sea or found it difficult to maintain their growth on the sandy sea floor. They were slowly broken up and their skeletal fragments were extensively abraded and redistributed through the sequence becoming smaller, rounder and more opaque in the higher parts of the formation.

During this time, detritus was derived from the underlying basalt possibly by both submarine and sub-aerial erosion, as well as from granites and sedimentary rocks in the vicinity.

While the Maude Basalt represents a period of local regression, the Upper Maude Limestone represents the following transgression. It will later be shown that this can be correlated with a similar change in environment at Batesford where evidence of transgression or deepening occurs near the top of the Batesford Limestone corresponding to the entry of *Lepidocyclina*. This heralded the beginning in both places of the deposition of the clays or deeper-water facies.

BATESFORD LIMESTONE

The Batesford Limestone includes all limestone, sandy limestone and calcareous sands which overlie Palaeozoic granite and diabase on the flanks of the Dog Rocks and underlie the Fyansford Clay. The type section is located in the present quarry of Australian Cement Ltd, S. of Batesford on the Moorabool R., where 110′ of limestone is exposed passing upwards to interbedded calcareous clays and marls which mark the transition to Fyansford Clay (Pl. XVII, fig. 1).

The limestone has been deposited in shallow water in which the Dog Rocks granite and diabase formed a small island. Slow submergence of the island in a transgressive sea has resulted in important lateral and vertical variations in facies which are reflected in the lithology, mineralogy and faunal content. The migration of the marine environments has resulted in diachronous lithologies as illustrated in Fig. 13.

The formation is at least 200′ thick in the vicinity of the quarry and extends SE. outcropping in the bed of the Moorabool R. until it passes beneath the river half-way between the quarry and Coghill's (section 3).

The limestone is well known through the writings of many authors (see references in Singleton 1941) who have studied the faunal assemblages contained in it. Of special interest are the larger foraminifera, *Lepidocyclina howchini* and *Cycloclypeus victoriensis*, which are extremely abundant in the upper part of the formation and have led to its use as the type section for the Batesfordian stage in the subdivision of the Tertiary of Victoria. Singleton (1941, p. 31) has defined the

TABLE 8

Percentage carbonate : sand : silt-clay ratios from Batesford Limestone

Sample No.*	% $CaCO_3$	% +240#	% −240#	+240#/−240#
601	60·9	36·8	2·3	15·7
602	55·2	42·2	2·5	16·8
603	83·2	15·0	1·7	8·9
604	76·4	20·9	2·6	7·7
605	63·6	34·1	2·2	15·5
606	86·7	12·2	1·8	6·7
607	61·5	36·4	2·0	18·0
608	68·0	30·5	1·5	20·0
609	44·3	49·2	6·5	7·6
610	83·9	13·4	2·6	5·4
611	82·6	7·8	9·5	0·8
612	95·5	1·27	3·2	0·4

* Samples taken at 10′ intervals up quarry face.

Batesfordian stage as 'the interval of time represented by the deposition of the *Lepidocyclina*-bearing limestones of the Batesford quarries . . .'. Since only the upper portions of the limestone contain the genera referred to, the lower limestones are excluded from the Batesfordian as defined.

Fresh outcrops show little trace of bedding. On weathered surfaces bedding can be seen to dip to the SE. at approximately 1-2° carrying the limestone below river level E. of the present quarry. The general shape and configuration of the limestone body is controlled by the topography of the granitic basement and dips are regarded as deposition effects accentuated by differential compaction. Some compaction effects are visible in the overlying clays appearing as local irregularities in bedding on the S. quarry face. These are sometimes related to slumping into caves and solution hollows occasionally encountered during quarrying operations (Pl. XVII, fig. 2).

LITHOLOGY: The limestone consists of accumulated skeletal fragments of polyzoa, echinoids, pelecypods, foraminifera and other organisms. Carbonate fragments are mostly in the sand-size range with some larger and well preserved fossils. Most of

TABLE 9

Sizing parameters of complete limestone samples and insoluble residues from Batesford Limestone

Graph No. on Fig 8 & 9	Sample No.	Md.	Q_3	Q_1	P_{10}	P_{90}	So	Sk
1	600 A	0·52	1·4	0·25	4·5	0·15	1·89	1·92
	B	0·52	1·60	0·20	3·00	—	2·83	1·18
2	599 A	0·22	0·38	0·14	0·61	0·10	1·65	1·10
	B	0·14	0·17	0·10	0·22	0·08	1·27	0·85
3	601 A	0·33	0·53	0·21	0·86	0·13	1·58	1·02
	B	0·27	0·46	0·19	0·80	0·10	1·55	1·20
4	603 A	0·32	0·51	0·20	0·82	0·12	1·58	0·98
	B	0·24	0·33	0·16	0·56	0·04	1·43	0·91
5	605 A	0·24	0·41	0·16	0·67	0·09	1·60	1·14
	B	0·21	0·29	0·15	0·47	0·09	1·39	0·98
6	607 A	0·27	0·47	0·18	0·76	0·10	1·61	1·16
	B	0·18	0·25	0·13	0·41	0·09	1·38	1·00
7	609 A	0·26	0·39	0·18	0·57	0·11	1·47	1·04
	B	0·21	0·30	0·14	0·45	0·05	1·46	0·95
8	610 A	0·43	0·77	0·23	1·3	0·11	1·83	0·95
	B	0·41	0·71	0·18	1·0	0·03	1·98	0·76
9	611 A	0·26	0·39	0·12	1·7	0·02	1·80	0·69
	B	0·07	0·37		2·0			
10	612 A	0·44	0·68	0·27	1·4	0·17	1·58	0·98
	B	residue was entirely silt-clay, therefore not sized on screens						

A...refers to the analyses of complete carbonate samples.
B...refers to the analyses of insoluble residues from the same samples.

TABLE 10

Heavy mineral assemblages from vertical section through the Batesford Limestone and Fyansford Clay outcropping at Batesford quarry

		Biotite	Chlorite	Garnet	Zircon	Ferro-dolomite	Tourmaline	Actinolite	Andalusite	Epidote	Anatase	Rutile	Brookite	Ceylonite	Topaz	Pale amphibole
SE 16	FYANSFORD CLAY				c		c					V	V	V	r	
SE 8			V		c		c				V	r	V			
SE 5			r		c		c				V	V	V	V		
SE 3			r	V	c		c	V								
SE 2		o	o	V	o		o					V	V			
610	BATESFORD LIMESTONE	A	o	r	r						V					
609		A	o	o	r				V	V						
607		A	c	o	r	V		V		V	V					
605		a	c	r	V	a		V								
603		A	c	o	r		V	o	V	V						
601		A	c	r	V	c	V	o	V							
599		A	c	o	r		V		V	V						
600		A	c	a	o		V	o	V							o

A...very abundant
a...abundant
c...common
o...occasional
r...rare
V...very rare

the larger organisms, especially polyzoa, have been comminuted and graded although many large fossils have been virtually deposited *in situ*. These show little or no signs of abrasion, indicating the gentle nature of the currents and the partly autocthanous nature of the deposit. However, most of the carbonate is clastic in origin and the limestone may be described as a biocalcarenite.

In thin section, fragments of poorly sorted organic remains occur with quartz, felspar, biotite and accessory minerals (Pl. XVII, fig. 3). Secondary carbonate is of minor importance appearing sometimes as a thin zone of sparry calcite around skeletal fragments. The limestone has remained little affected by lithification and diagenesis being mostly soft and friable.

Carbonate usually occurs as calcite with the exception of aragonitic lamellibranch shells. Tests for dolomite have proved negative with the exception of rhomb-shaped crystals in the heavy mineral fraction (sample 605) which represent a local secondary development of ankerite or ferro-dolomite (Table 10).

LATERAL VARIATIONS: Detailed sedimentary petrology shows considerable lateral variations in sizing, in the nature and percentage of insoluble residues and in overall carbonate content.

In an outcrop W. of the present quarry, limestone directly overlies granite (sample 613). This limestone is very impure, containing large composite grains of quartz and felspar in a bluff-red carbonate matrix. The matrix is sub-opaque and contains a high percentage of clay with lime-mud filling the interstices between skeletal fragments. Very poor sorting is indicated by the association of coarse granitic detritus with the fine-grained, opaque, clay-size material. The low carbonate content is here associated with poor sorting. In fact, sorting has been an important factor in determining the quality of the limestone throughout the deposit.

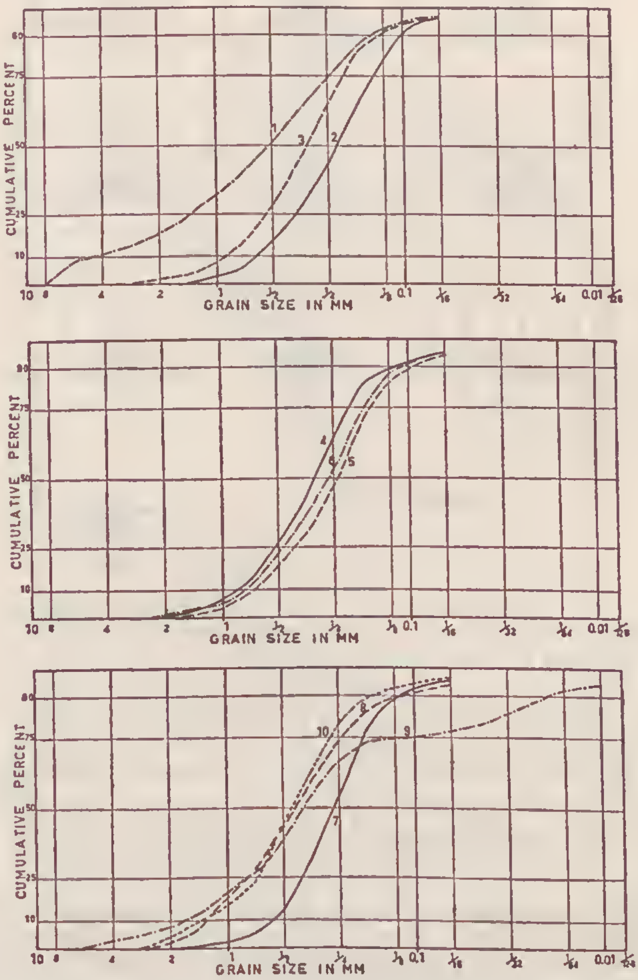


Fig. 8—Cumulative percentage curves showing the size distribution of complete samples from the Batesford Limestone. Graph numbers refer to samples listed in Table 9 with sizing parameters and located in Fig. 19.

In the quarry, samples 600, 599 and 601, represented by graphs 1-3 in Fig. 8, 9, were selected from the same level on the quarry floor but in increasing distance away from the granite.

The size analyses of these complete samples, including carbonate, indicates a considerable decrease in grain size of clastic material away from shoreline; the median diameters fall from 0·52 mm to 0·22 mm over a distance of some 100 yds.

Sorting coefficients (So) likewise indicate better sorting with increasing distance

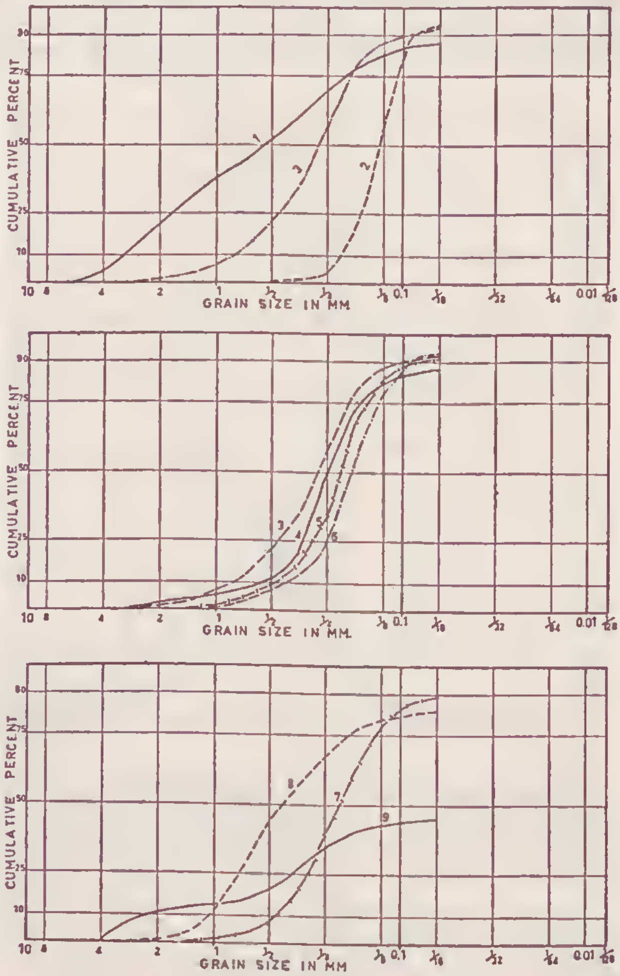


Fig. 9—Cumulative percentage curves showing the size distribution of the insoluble residues obtained by treating in dilute HCl. Parameters of insoluble residue analyses are shown with sample numbers in Table 9. The samples treated are identical with those shown in Fig. 8.

Note the tendency towards smaller grain size in graphs 3 to 6 corresponding to increasing height in the section. Graphs 1 to 3 from samples from quarry floor; graphs 3 to 9 from samples at intervals up the quarry face; as shown in Fig. 19.

away from the granite. Values decrease from 1·87 to 1·65 to 1·58 for graphs 1, 2, and 3 respectively (Table 9).

The size analyses of insoluble residues reflect similar trends, although sample 599 is somewhat anomolous in that it has a smaller median diameter than any other insoluble residues from the entire quarry. Apart from this, the overall trends are the same as those evident in analyses of complete samples, which indicate better sorting and smaller sizes deposited away from the shoreline on the Dog Rocks granite.

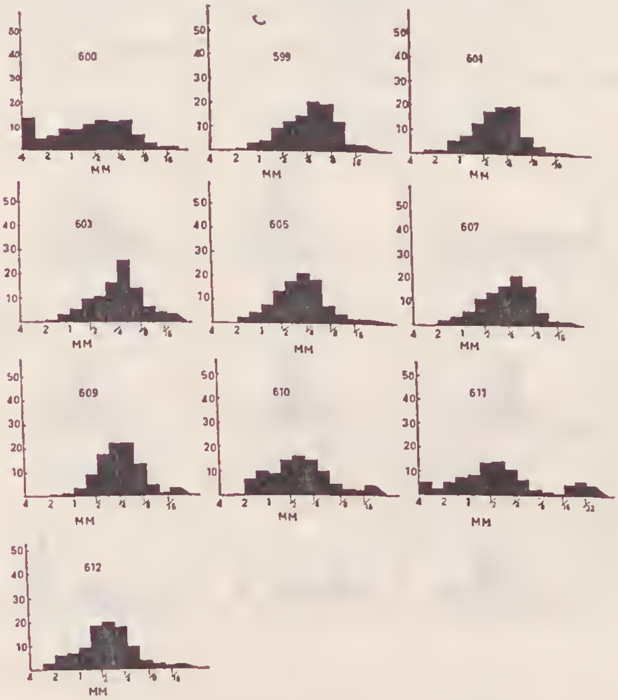


Fig. 10—Histograms showing percentage distribution of grain sizes of complete samples from the Batesford Limestone. Samples are identical with those represented on Fig. 8. For parameters see Table 9, and for location of samples see Fig. 19.

Insoluble residues consisting of quartz, plagioclase, microcline, biotite and muscovite with accessory minerals, most of which appear in the heavy fraction, also show lateral variation away from the shoreline. Near the granite, composite grains of quartz and felspar to 3 mm are common but these become progressively rarer to the E. Changes in grain size are also noticeable in the heavy minerals especially in the garnets which are considerably larger near the granite than in other parts of the quarry. Two types of prismatic amphiboles occur but become progressively rarer away from the granite. An unidentified pale acicular amphibole recorded in sample 600 (Table 10) is entirely absent from samples taken from the E. quarry face. The frequency of actinolite also declines rapidly in the same direction, due to increasing distance from the diabase source associated with the granite.

Carbonate content increases away from the granite in inverse relationship to the decrease in the percentage of detrital quartz and felspar. Percentages range from

55·5 carbonate (600) to 59·0 (599) to 60·9 (601) for these samples on the quarry floor.

Vertical Variations: With increasing height in the formation above the quarry floor, sizing becomes more efficient, carbonate percentages tend to rise and small variations occur in the percentage of heavy mineral species present.

In the lower 70′ of limestone exposed in the quarry, granitic detrital quartz and felspar grains are associated in all samples with porous skeletal carbonate remains of lamellibranchs, polyzoa, echinoid tests and spines, and the tests of small foraminifera. Almost the entire calcite present is in the form of skeletal material. In thin section, the limestone is a well washed porous rock devoid of fine-grained lime mud matrix and lacking secondary cement.

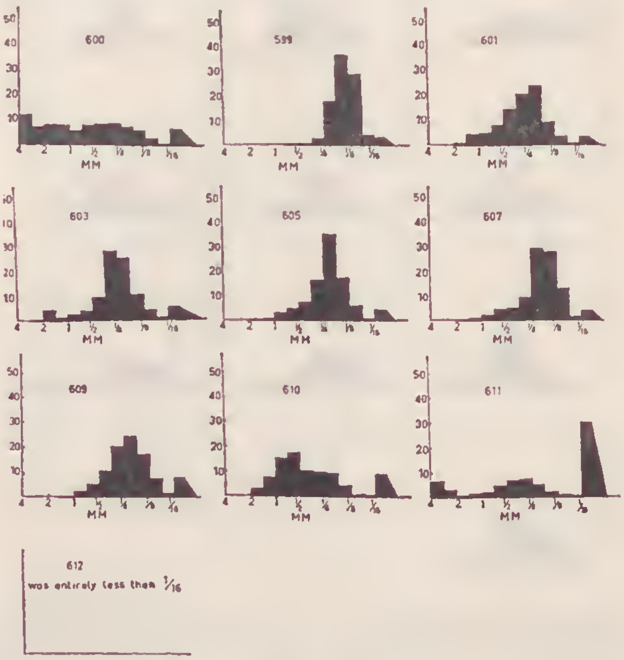


Fig. 11—Histograms showing the percentage distribution of grain sizes of insoluble residues from the same Batesford Limestone as those represented in Fig. 10. Samples were treated in dilute HCl. The size distribution of the residues obtained is illustrated above and in Fig. 9. Note the high proportion with diameter less than 1/10 mm in samples 609, 610, 611 and 612 from the upper 40′ of the quarry face.

The sorting coefficients remain approximately constant in this lower 70′ at values near 1·60, although the sizing of insoluble residues indicates progressively better sorting with increasing height in the section. These latter values decrease from 1·55 on the floor of the quarry to 1·38 in sample 607 from 60′ above the floor (Table 9).

While sorting becomes more efficient, the size of median diameters shows consistent decrease. This trend is evident in the analyses of both complete samples and insoluble residues from the quarry floor to 80′ above it. The median diameters of the total samples fall from 0·33 to 0·27 mm whilst those of the insoluble residues fall from 0·27 to 0·18 mm.

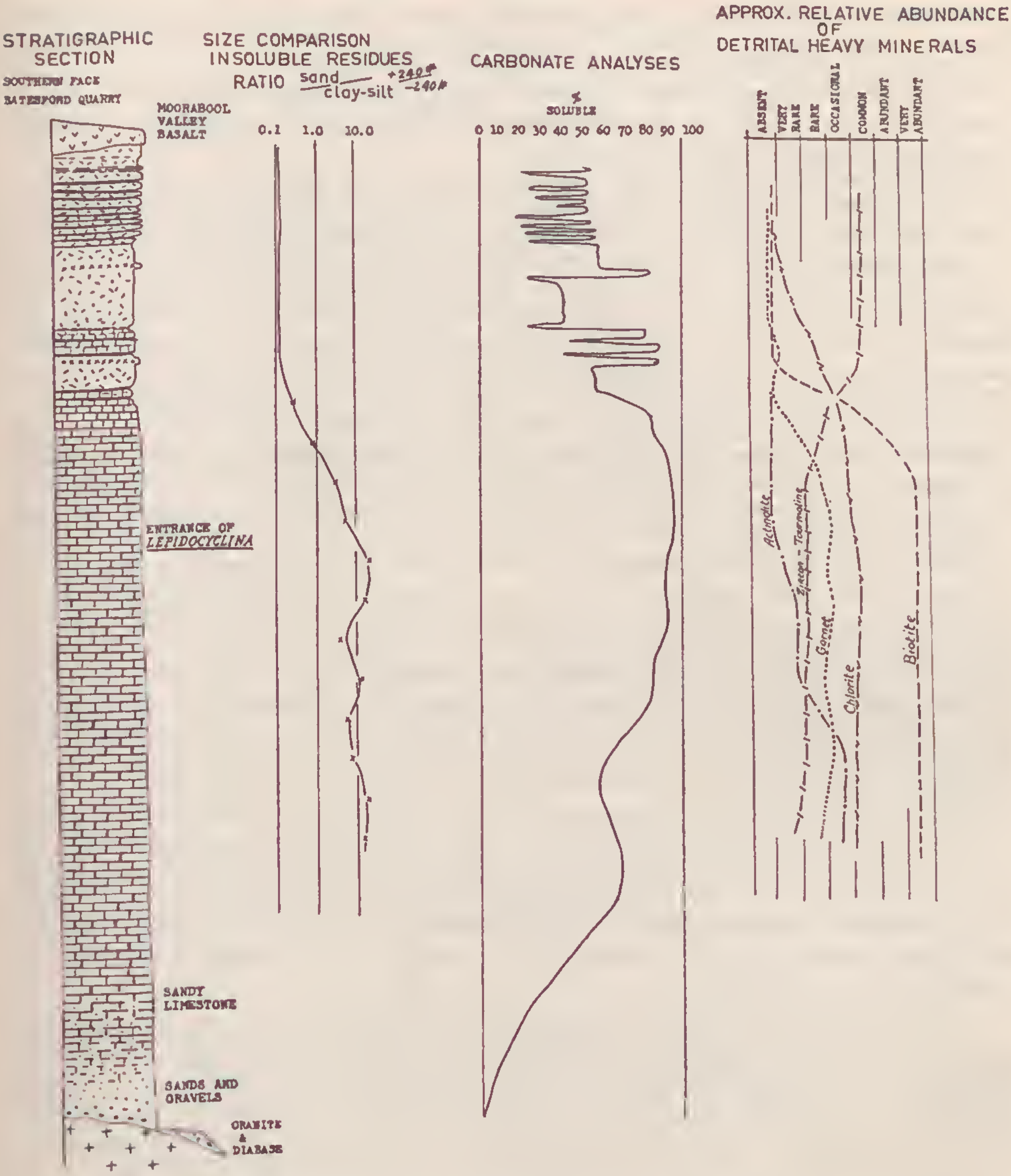


Fig. 12—Graphs showing vertical variations through the Batesford Limestone and Fyansford Clay as exposed in section on the S. face of the limestone quarry at Batesford. Changing sedimentary conditions are evident in the upper part of the limestone as shown partly by the change in the grain size of insoluble residues. The disappearance of granite detritus is shown by the decrease in abundance of biotite at the top of the limestone and absence of sand-size detritus. This is thought to correspond to a deepening of the sea and complete submergence of the adjacent granite island during Lower to Middle Miocene transgression.

Graphs 3-6 (Fig. 8, 9) show the consistent trend towards finer material and better sorting, whilst graphs 7-9 temporarily reverse the trend, first becoming coarser then rapidly becoming very fine with poor sorting.

The principal change in the occurrence of detrital minerals in the lower portion is seen in the heavy mineral analyses showing a decrease in the percentage of actinolite with increasing height in the section.

The graph in Fig. 12 indicates that the carbonate content generally increases up the quarry face, reaching a maximum with the entry of *Lepidocyclina* towards the top of the formation. Other important changes also appear at this level.

Approximately 40′ below the top of the formation (70′ above quarry floor) quartzose and felspathic detritus is rare but clay increases markedly. This change is indicated in Fig. 12 by the graph representing the ratio of sand (+240 mesh) to clay-silt (—240 mesh) in the insoluble residues. This change is also reflected in the poorer sorting of insoluble residues in the upper portion commencing with sample 609 to 610 and 611 (sorting coefficients 1·46, 1·98 and 1·80 respectively).

The entry of the larger foraminifera at the base of this upper zone is largely responsible for the increase in grain size of the carbonate skeletal fragments, apparent in graphs 8, 9 and 10 of Fig. 8, and in the median diameters of corresponding samples in Table 9. In this zone, most carbonate greater than 1 mm often consists of foraminiferal tests.

With the entry of clay into the insoluble fraction at 80′ above the quarry floor, zircons become more abundant in the heavy mineral suite and the percentage of garnet declines. This trend is maintained through this upper zone until, at the top of the limestone, the whole heavy mineral suite undergoes important changes. The typical granitic suite of biotite, chlorite, muscovite and garnet disappears, giving way to a suite of minerals characterized by tourmaline, and minerals of the titanium group. Since tourmaline is very rare in the granitic suite in the lower parts of the quarry, and is rarely present in the related granite of the You Yangs (Baker 1935), the clays in which it occurs must be derived from a source other than granite.

The top of the formation is often marked by a hard non-porous band of limestone 1 to 2 ft thick which weathers to a buff pink colour. In thin section, this consists of skeletal remains in which the cavities have been almost completely infilled by finely divided lime mud associated with a high percentage of clay. This fine matrix forms a very effective cement accounting for the hardness of the bed. It is further evidence of the poor sorting which accompanied the transition of limestone to clay in this vertical variation in facies.

Faunas: The faunas present throughout the limestone are principally benthonic forms suitable to a clear water environment with sandy sea floor. Burrowing mollusca are rare, *Lepidocyclina* and *Cycloclypeus* would find survival difficult in muddy conditions although they do persist for some 10′ into the overlying clays as recorded by Carter (1963). Traces of *Lithothamnion* occur in the limestone and were probably derived from the granitic shoreline on which these algae developed.

Discussion: The Dog Rocks granite was exposed as an island in the Tertiary sea at the time of deposition of the Batesford Limestone. This is borne out by the abundance of granitic detritus in the marginal parts of the limestone, by the limestone facies which reflect a shallow water neritic environment, and by the limestone upper level which occurs 200′ below the summit of the Dog Rocks.

The overall structure is one of lensing or wedging out against the shoreline. Lateral variations in the limestone are due principally to variation in marine sorting capacities away from the shoreline. In the lower part of the limestone, currents were sufficiently strong to winnow out clay-size material and to redistribute comminuted quartz and felspar away from the shoreline. Clays have been carried further off-shore and deposited in quieter waters, while the coarsest material was deposited close in-shore. It is known that near the outer margins of the deposit a lateral facies change from limestone to silty-clay occurs corresponding to increasing distance away from shoreline as would be expected. This change occurs gradually and is the final result of the trend already evident in a small way in the limestone of the quarry, a trend towards decrease in grain size away from shoreline. This lateral gradation in grain size is probably a result of deeper water away from shoreline and corresponding variation in the strength of bottom currents.

Similarly in the vertical variations, the appearance of clays associated with other facies changes at the top of the limestone, must have been due to a change in the marine conditions which produced weaker currents. The nature of the change was a deepening of the sea around the Dog Rocks. It has been shown in the study of the detrital minerals that the granitic and diabasic suite, quartz, felspar, biotite, garnet and amphiboles, almost completely disappears near the top of the limestone and is replaced by clays with accessory tourmaline, zircons and titanium minerals. The granite then ceased to be a source of detritus and must have been below the zone of high energy wave activity which eroded granite in the littoral zone during the accumulation of the main body of the limestone. This change could only occur by complete submergence in a deepening sea.

It is significant that the changes in environment which eventually resulted in the extinction of the prolific faunas near the Dog Rocks, can be initially detected in the limestone well below the transition to Fyansford Clay. These changes correspond to the entry of *Lepidocyclina* 40′ below the clay and are characterized principally by the decline in granitic detritus. This indicates a decrease in the exposed area of granitic landmass on the Dog Rocks. Slow deepening of the basin had resulted in a progressive transgression of the sea on to the granite slowly submerging it. This deepening probably corresponded to the transgressive phase at Maude and reached a climax which coincided with the top of the Batesford Limestone and resulted in changes in bottom conditions with poorer sorting, muddy environment and important faunal changes.

During the deposition of the Batesford Limestone, a regular gradation in grain size existed on the sea floor from coarse to fine away from shoreline, corresponding to the lateral changes now evident along any one horizon. A similar off-shore gradation is commonly recorded from modern marine environments (Gould and Stewart 1955, Byrne and Emery 1960) although many exceptions are known.

The near-shore zone at the Dog Rocks became admirably suited to the development of a calcareous facies for in such a zone the following conditions were fulfilled:

1. Carbonate solubility would be low in the shallow warm water, thus facilitating its extract by shelly faunas.

2. Active currents continuously removed fines and maintained clear sandy bottom favourable to benthonic organisms.

3. Highly aerated and oxidizing conditions in the water and on the sea floor, together with photosynthesizing algae and phytoplankton, would provide abundant food and oxygen to support a dense population on the sea floor.

The thick deposit of limestone which accumulated under these conditions managed to maintain relatively uniform sorting characteristics (at least below the top 40′). This indicates that approximately constant depth was maintained, in which case the rate of deposition must have approximated the rate of deepening due to transgression.

The sequence of depositional events is summarized and illustrated in Fig. 13.

FYANSFORD CLAY

This formation derives its name from the section in the road cutting on the Inverleigh Rd at Fyansford, often referred to in earlier literature as 'Orphanage Hill'. The formation is defined here to include all clays, argillaceous limestone, marls and argillaceous silts situated above the stratigraphic level of the Batesford Limestone and below the disconformable contact with the Moorabool Viaduct Sands.

The maximum outcrop thickness occurs in the section at Fyansford (No. 2) where 112′ have been measured in the road cutting. Here the base of the formation is not exposed, but the upper contact with the Viaduct Sands is visible near the top of the sequence and is marked by a phosphatic nodule band.

The lower formation boundary is best seen in the quarry at Batesford or in the cliff section on the N. side of the river near the quarry. Here beds of clay interdigitate with beds of limestone in a transition zone between the Batesford Limestone and Fyansford Clay. When traced laterally, each interfingering bed shows facies variations from argillaceous to more calcareous sediment or vice versa. The transition between the two formations is thus gradational, both vertically and laterally. Under these circumstances it is not possible to specify any bed as a precise formation boundary.

Facies variations occur within the Fyansford Clay, but the predominantly argillaceous lithology forms a very widespread and persistent unit throughout the area. It can be traced along the Moorabool, Barwon and Leigh R. lensing out to the N. on rising Lower Tertiary sediments. Near Maude it overlies Upper Maude Limestone, but unfortunately exposures in this area are very poor and detailed study has been necessarily limited to the Geelong area.

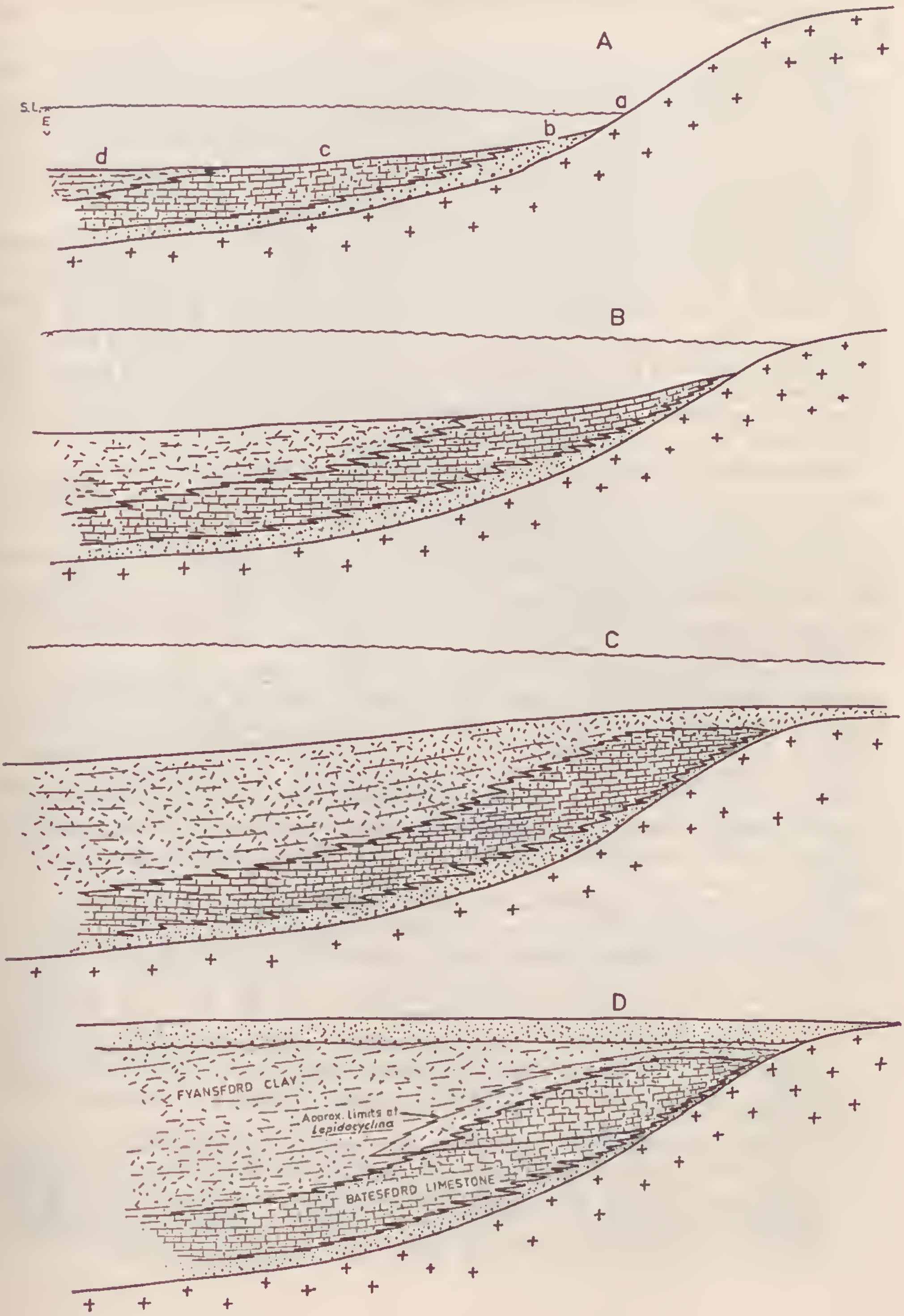
Fig. 13—Diagrams illustrating the development of the diachronous relationships between the Batesford Limestone and Fyansford Clay.

A. In Lower Tertiary, possibly Janjukian time, transgressive advance of shoreline occurred cross granitic terrain near Dog Rocks. Four environments are represented in the sedimentary facies of the limestone-clay association. Abraded *Lithothamnion* fragments occur throughout the limestone from a rocky littoral zone (a). Coarse marginal sands, now separating limestone from granite, represent a zone of coarse-grained granitic detritus deposited close in-shore with coarse skeletal carbonate sands (zone b). Reworked skeletal carbonate and comminuted granitic detritus were deposited in shallow off-shore zones by currents of medium carrying and sorting capacity (zone c). Clays and fine-grained abraded carbonate were transported away from shoreline and deposited by weaker currents in deeper water (zone d).

B. Sedimentation under these conditions kept pace with and may have slightly exceeded the rate of deepening. The large benthonic foraminifera, *Lepidocyclina* and *Cycloclypeus* appeared for the first time and an increase in the rate of deepening is indicated by deterioration in sorting and a decline in the percentage and size of granitic detritus corresponding to submergence of the granite.

C. The rate of deepening during maximum transgression considerably exceeded the rate of deposition. Deeper water lead to weaker currents, poorer sorting and a muddy environment. Benthonic foraminifera were smothered and reducing conditions developed in the clays on the sea floor with the development of pyrite and glauconite.

D. During the regressive phase, gently dipping clays were eroded and horizontal Moorabool Viaduct Sands were deposited on them with a small angular unconformity. Initial off-shore dips in limestone and clay would be accentuated by differential compaction.


A
S.L.
a
b
c
d
B
C
D
FYANSFORD CLAY
Approx. limits of
Lepidocyclina
BATESFORD LIMESTONE

A maximum known thickness of 300′ of clay is present near Coghill's (section No. 3).

General Lithology: Occasional bands of harder, limonitic and usually more calcareous beds are interbedded with thicker beds of heavy grey calcareous clay (section 2). In outcrops exposed for long periods, such as that at Fyansford, the softer clays are pale grey while the harder beds are limonitic yellow. But in more recently excavated material, such as in the Batesford quarry or in bores, the clays are dark grey and the calcareous bands are merely light grey. Therefore most of the colour variations in the older outcrops are due to weathering.

Beds are usually horizontal but in the section in the cliff N. of the Batesford limestone quarry where clay is exposed for some 100 yds, a slight dip to the SE. of approximately 2° is apparent. This follows a similar trend in the underlying limestone which carries the clay-limestone contact below the level of alluvium a short distance to the E. of the present quarry. This dip was noted by Hall and Pritchard (1897) and was taken to infer a regional easterly dip. The pronounced increase in thickness towards the E. towards Coghill's is thought to be due to the easterly dip of the Tertiary sediments following granitic basement. This trend is important in the discussion of the age of the clays E. of Batesford.

Origin of Dip: The fact that the dip follows the trend of the underlying granitic basement which slopes to the E. indicates that it may be a depositional effect controlled by the basement topography as suggested for the Batesford Limestone. This would imply that the easterly dip would not be maintained around the entire granite body but would tend to occur radially away from the granite. Suitable outcrops are not available on the N. and W. sides of the Dog Rocks to check this theory. Initial dip of similar amount has been recorded by Koldewijn (1958) in clays (pelites) on the Paria-Trinidad shelf, especially close to shoreline.

The alternative explanation would involve slight tectonic movements in epi-Cheltenhamian time, for the younger sands which overlie the clays are horizontal. However, the known active faults in the region have moved in such a way as to produce a westerly rather than easterly dip. Moreover, if the dip is tectonic in origin, it should persist regionally to the N. of the Dog Rocks, in which case the sediments at Clay Point should be considerably older than the sediments at Fyansford or Batesford. There is no evidence to support this; on the contrary, the evidence suggests that they are at least younger than the clays exposed in the quarry at Batesford.

The dip is therefore regarded as an initial rather than tectonic effect.

Carbonate Content: From the results of detailed carbonate analyses (see Tables 12-14), the following general conclusions have been reached:—

1. The overall carbonate percentage decreases vertically above the Batesford Limestone reaching its lowest average values in the Fyansford section. Thereafter, it tends to increase in the younger sediments as at North Shore, Corio Bay. Even in the Fyansford section, there is a tendency for the carbonate content to rise in the samples from near the top (F7, F11, F10, F12, Table 13).
2. The limestone junction is not a sharp one as observed by Hall and Pritchard, but is rather a transitional one of interbedded clay and limestone with some thick bands of marl. The actual transition commences below the top of the quarry in the limestone as indicated by the insoluble residue analyses, and is marked by the prominence of clay in the upper 40′ of the limestone.

3. In weathered outcrop, the marl bands tend to be more limonitic in colour and appearance, and conversely, the more yellow clays as at Clay Point, and Corio Bay, tend to be higher in the percentage of carbonate than the grey clays. These limonitic clays are also significantly coarser than the dark grey clays. This is evident in the analyses of sand : silt-clay ratios in Tables 12-14.
4. The principal source of calcium carbonate is the skeletal remains of the abundant benthonic mollusca, and to a lesser extent, pelagic foraminifera and polyzoa which found a suitable habitat in the Miocene sea. Mollusca are often entire, showing no evidence of transport. In any case, the currents which deposited the fine-grained clays and silts would not have been sufficiently strong to have transported molluscan shells. The carbonate is therefore mainly autochthonous. However, some fine-grained clay-size carbonate or lime mud has been transported and deposited with clay minerals. This fine-grained carbonate could originate in three ways:

   (a) By abrasion of skeletal remains of polyzoa, mollusca, etc., in the shallow in-shore zones giving rise to a fine carbonate 'flour' which would be deposited off-shore with clay-size material, e.g. the fine fraction, equivalent to sand-size carbonate of the Batesford Limestone.

   (b) By organic precipitation, principally by algae, as minute aragonite needles.

   (c) By chemical precipitation as aragonite in shallow warm water.

   Whilst it is impossible to give any definitive explanation of the origin of this lime mud, it is almost certain that carbonate of type (a) is present. The presence of coralline algae in the organic remains in the limestones and marls suggests that lime secreting algae may have produced carbonate of type (b). But there is a complete absence of evidence to suggest chemical precipitation of type (c).
5. The density of the benthonic population, the shells of which largely make up the carbonate content, was largely controlled by the aeration of the sea floor. The lime rich bands are probably related therefore to periods of better aeration and higher oxidation potential. This is supported by mineralogical evidence (see facies summary, Table 15).

Size Analyses—Sand : Silt-Clay Ratios: The results obtained by sizing insoluble fractions through a 240 mesh screen are set out in Table 11. Although the actual silt percentage was not measured, a visual approximation was made by examining the —240 mesh fraction under a binocular microscope after decanting clays in suspension. In all cases the percentage of silt estimated has been found to be approximately proportional to the percentage sand or coarse fraction retained on the 240 mesh screen.

Table 11

Approx. % of sand, silt and clay from various outcrops of Fyansford Clay

Locality	Average % sand + 240 mesh	Approx. clay content	Approx. silt content	Approx. sand content
Clay above Batesford quarry	1·4	v. high	v. low	v. low
Fyansford	5·6	high	high	low
Clay Point	11·0	medium	v. high	medium
Western Beach	16·0	medium	v. high	high
North Shore	32·0	low	v. high	v. high

These results are set out from top to bottom in increasing percentage of coarse material. A significant feature which emerges from this arrangement is that the oldest clays, those associated with *Lepidocyclina* at Batesford and Batesfordian in age, are at one end of the table, and the youngest, those with *Hinnites* at North Shore and of Bairnsdalian age, are at the end. This does not necessarily mean that the intervening localities are in their correct relative orders of age, but it does reflect important changes in sedimentation associated with the filling of the Tertiary basin, and the shallowing of the sea. No doubt lateral variations will complicate the picture but this trend towards increasing coarseness does take place throughout any one vertical sequence in the area, i.e. a sandy facies of the Fyansford Clay occurs towards the top of the formation.

SUMMARY OF MINERALOGY: The clay mineralogy has not been studied. Investigation has been limited to insoluble residues other than clays.

The principal residues remaining after treatment in dilute acid and decantation of the clay fraction, are finely divided quartz, muscovite, chloritic biotite, magnetite and ilmenite with variable amounts of fresh biotite from some samples only.

TABLE 12

Ratio of carbonate : sand : silt-clay from Fyansford Clay outcropping above Batesford Limestone in the cement quarry, Batesford

Sample No.	% $CaCO_3$	% +240#	% −240#	+240#/ −240#	Residues
SE 2	59·2	0·8	40·0	0·05	quartz, muscovite, chloritic biotite
SE 3	89·0	0·2	10·8	0·02	*idem* with fresh biotite
SE 4	81·0	0·2	18·8	0·01	*idem*
SE 5	26·5	1·4	72·1	0·02	*idem* with pyrite
SE 6	41·5	1·2	57·3	0·02	quartz, muscovite chloritic biotite
SE 8	24·8	8·0	67·2	0·1	*idem*
SE 9	84·7	0·6	14·7	0·04	*idem* with glauconitic casts
SE 15	59·1	0·6	40·3	0·01	quartz, muscovite, chloritic biotite and fresh biotite
SE 16	18·6	0·7	80·7	0·01	*idem*
SE 17	53·6	0·6	45·8	0·01	*idem*

The heavy mineral content consists mainly of a mature assemblage of zircons, tourmalines and rutile with leucoxene, iron ores and a small amount of topaz. This further reflects the low topography and advanced weathering which must have existed in the area of the source rocks. This assemblage is not diagnostic of any particular source area and has not been studied in detail.

Three minerals of special interest which occur in the clay are siderite, pyrite and glauconite.

Siderite is recorded in samples of the clays from Clay Point, Batesford and Fyansford. It occurs as minute rhombohedra approximately 0·02 mm diameter showing strong red-brown iron-staining due to oxidation. When seen fresh in bore cores it is colourless. Its euhedral shape and its abundance in suspected faecal pellets indicate that it has developed *in situ* after the pellets formed. It represents a reducing environment as shown by Teichert (1958) and is regarded here as having developed in the sediment below the water interface in a zone of poor aeration, i.e. an authigenic mineral originating very soon after burial.

Pyrite has been observed in dark clays immediately overlying the limestone at the Batesford quarry. In some samples it is associated with glauconite. It occurs as small irregular nodules down to spherulites of sub-microscopic size less than 5 microns diameter. It is regarded as a reasonable environmental indicator reflecting alkaline pH with anaerobic and reducing conditions as suggested by Edwards and Baker (1951) and confirmed by later workers. Conditions of poor aeration are also indicated by the paucity of organic remains in any bands which are pyritic. The almost perfect preservation of molluscan shells with nacreous layers intact confirms the alkaline pH of the sediment.

TABLE 13

Ratios of carbonate : sand : silt-clay from Fyansford Clay in road cutting at Fyansford

Sample No.	% $CaCO_3$	% +240♯	% −240♯	+240♯/−240♯	Residues
F 1	8·2	9·2	82·6	0·11	quartz, muscovite, chloritic biotite
F 3	8·4	3·6	88·0	0·04	*idem* with traces glauconite and euhedral siderite
F 4	8·9	8·8	82·3	0·01	quartz, muscovite, chloritic-biotite
F 6	7·8	2·8	89·4	0·03	*idem*
F 8	4·1	3·2	92·7	0·03	*idem*
F 7	20·9	6·4	72·7	0·09	*idem*
F 11	7·3	1·2	91·5	0·01	*idem*
F 10	31·1	5·6	63·3	0·09	*idem*
F 12	17·3	10·0	72·7	0·14	*idem*

Glauconite also occurs above the limestone in the Batesford quarry (SE.9, SE.10) and in a relatively similar position with respect to the limestone in a bore near Coghill's at 138′ below the surface. It is also recorded in insoluble residues from the clays at Fyansford (F.3). It occurs as discrete pellets, infilling foraminiferal and polyzoan chambers and as an unusual, massive streaky lenticular green mineral. In the latter mode of occurrence it shows distinct pleochrism. Ample iron and potassium were available in the environment with minerals derived from nearby granite, with pyrite and normal clay minerals to provide for the formation of glauconite. In places, streaks to ⅛″ thick occur, which are much too large to have developed from mica booklets as observed by Hadding (1932). It is more probably derived directly from illite or montmorillonite taking up potassium and iron in a favourable environment of slow deposition as suggested by Cloud (1955), Burst (1958) and others.

Glauconite itself is not a good indicator of environment for it can form under a very wide range of conditions which are not at all well understood. Whilst favouring development in neritic or shelf seas, it does not develop in shoreline or near-shore environments which support polyzoa or reef building algae as pointed out by Cloud (op. cit.). It favours rather intermediate depths or deeper neritic zones.

Its occurrence at Batesford immediately above the limestone in which polyzoa abound, further indicates a marked deepening of the Miocene sea at the conclusion of deposition of the Batesford Limestone.

At the horizon in which glauconite is most prominent, i.e. in the basal portion of the clay sequence, there is almost a complete absence of sand or even silt-size quartz. This suggests extremely weak bottom currents and very slow terrigenous sedimentation. This is in contrast with the upper portion of the clay sequence where silt and sand becomes prominent in the clays and glauconite is absent.

TABLE 14

Ratios of carbonate : sand : silt-clay from the silty and calcareous facies of Fyansford Clay and overlying Viaduct Sands above the disconformity on the shores of Corio Bay

Sample No.	Location	% Ratios			Approximate Ratio Sand/ Silt-Clay
		Carbonate	Sand	Silt-Clay	
1/1A	Clay from basal 15′ Western Beach	28·6	26·0	45·4	1 : 1·8
2/1A	Marl from bed above 15′ Western Beach	57·8	10·2	32·0	1:3
1/1	From *Hinnites* bed at base of section, North Shore	61·4	25·4	13·2	2:1
2/1	Clay from above *Hinnites* bed at North Shore	11·2	38·6	50·2	3:4
DISCONFORMITY					
3/1	Sandy limestone from Rly cutting, Cowies Cr., Geelong	74·2	24·0	1·8	14:1
4/1	Sandy limestone at top of section, North Shore	69·8	21·4	8·8	5:2

One other feature worthy of note is the presence of small brown phosphatic concretions in the sandy clays at Clay Point. Mr A. Coulson first drew the author's attention to these in relation to the origin of the overlying bed of phosphate nodules.

The concretions appear as small dark brown bodies which tend to weather out slightly on the face of the cliff. They are not common however, and are not nearly as prominent as the large hard concretions in the Miocene clays and limestone at the Amphitheatre, N. of Shelford. Those at Clay Point grade outwards into clay and are clearly diagenetic rather than depositional in their origin.

FAUNAL VARIATIONS: A marked faunal change is associated with the transition at the top of the Batesford Limestone. The prolific population of benthonic foraminifera, *Lepidocyclina* and *Cycloclypeus*, required clear and probably shallow water to survive. *Lepidocyclina* continues for some 10′ into the clays before its final disappearance.

The vertical change in facies from limestone to clay reflects the deepening of the water in the basin. This was accompanied by two effects, either of which would probably have been sufficient to have accounted for the extinction of these benthonic foraminifera.

The first was the development of a muddy sea floor instead of a clear sandy bottom normally required for these genera. The second effect was a probable change in bottom temperature. In the Miocene of Victoria and New Zealand, *Lepidocyclina*, which is a tropical form, was near the most southerly limit of its endurance. Under these conditions, it is feasible that a slight change in bottom temperature due to a change in local environment, such as deepening of water during transgression, would be sufficient to cause extinction of the genus in the new environment.

These then give way to a muddy bottom molluscan fauna characterized by abundant gasteropods with polyzoa, brachiopods and lamellibranchs (see Hall and Pritchard 1892).

Within the molluscan fauna of the clays, oysters are common at Clay Point and at North Shore, Corio Bay. The latter is Bairnsdalian and certainly younger than the basal portion of the Fyansford Clay. At both these localities shallow water is indicated both from the abundance of oysters and in the high proportion of carbonate and sand relative to clay. The large pelecypod, *Hinnites corioensis*, is recorded from both localities and also from the section at Coghill's, by Hall and Pritchard (1892). Shallow water developed due to the slow infilling of the basin and later due to slight uplift, which eventually lead to the retreat of the sea from the area, and it is implied that these shallow water sediments are probably younger than the basal clays of Fyansford which, in turn, are certainly younger than the clays which contain *Lepidocyclina* at their base in the Batesford quarry.

It has been pointed out recently by Carter (1963) that his Faunal Unit 11, including *Orbulina universa* and *Cibicides victoriensis*, occurs throughout the outcrop of Fyansford Clay in the road cutting at Fyansford, which is regarded therefore by him as post-Balcombian (or Bairnsdalian). The Balcombian stage, on his determinations, is represented by approximately 30′ of clays containing *Globigerinoides transitoria* and *Orbulina suturalis* overlying the Batesford Limestone at the quarry.

FACIES VARIANTS OF THE FYANSFORD CLAY

Western Beach-North Shore Sections: Almost continuous exposures of silty-clay, marls and sandy limestones occur in the cliffs along the W. margin of Corio Bay. At North Shore, on the N. side of the entrance of Cowies Cr., a basal sandy limestone with *Hinnites* passes up to calcareous silts and clays with interbedded sandy limestone in the sequence below the nodule bed.

This sequence is related to a sequence exposed in the cliffs at Western Beach, Corio Bay (near Rippleside Park, 2 m. S. of North Shore) by almost identical stratigraphic position and lateral facies variations. Stratigraphically, the North Shore beds rise slightly to the S. and are equivalent to approximately the top 10′ of the Western Beach section below the nodule bed. This is accompanied by an increase in clay content laterally along the outcrop towards Western Beach. The carbonate percentage of the *Hinnites* limestone bed decreases, clay content increases, and *Hinnites* occurrence becomes less abundant being rarely found S. of Cowie's Cr.

Lithologically, the beds at North Shore and Western Beach are distinct from the clays in the Fyansford section, as well as being distinct from each other. The North Shore beds consist of sandy limestones with calcareous silts and a relatively low percentage clay. The Western Beach sediments are mainly sandy or silty marls interbedded in calcareous silty clays.

In both cases, a considerably higher percentage carbonate is associated with coarser detrital material than occurs in the clays in the Fyansford section. The beds along the W. shores of Corio Bay therefore represent a sandy calcareous facies of the Fyansford Clay, with those at Western Beach being intermediate in composition between the limestone beds at North Shore and the clays at Fyansford.

Stratigraphically, the main part of the Western Beach section passes under that of North Shore. Both are thought to be higher in the sequence than the beds at Fyansford; certainly higher than the lower part of the Fyansford section. A progressive vertical increase in both carbonate and sand content through the sequence of the Fyansford Clay therefore is apparent.

Marl Facies near Lethbridge: Near the top of stratigraphic section 13 (R.L.446′) SE. of Lethbridge, fragments of an indurated marl outcrop in broken blocks on the upper valley slopes. The exact thickness of the marl is uncertain but several closely spaced beds 1′ to 3′ thick are interbedded with calcareous clay. A few yards up the slope from the marl, rounded white quartz gravels and ferruginous sandstone blocks are found in the soil. The marl therefore occurs very close to the top of the Fyansford Clay. The band may be traced as broken blocks in soil to the N. and S. of this section but poor exposures prevent accurate determinations of extent and thickness.

In sample 3/16·5 from this section, the marl yielded tests of *Lepidocyclina*. These occur 110′ above the Maude Basalt and approximately 80′ above the Upper Maude Limestone. The occurrence of this genus, near the top of the clay sequence which is thought to be Balcombian or younger, puts it well above the stratigraphic level of its normal occurrence which is in sediments of Batesfordian age, equivalent in part to the Upper Maude Limestone.

The tests recovered from this sample have an abraded and rolled appearance. Some of their outer chambers and the outer equatorial margins have been eroded, resulting in an oval or elliptical cross-section rather than the normal discoidal shape; in addition, all tests have been deeply iron stained.

The horizon on which they occur is very close to the level of the disconformity with phosphatic nodules, along which much reworking and redistribution of older sediments is known to have taken place. Unfortunately, in the poor outcrop, the accurate relationships between the disconformity and the marl cannot be ascertained.

It is concluded that these foraminifera are *remanié* as suggested by their abraded appearance and position in the sequence. They have probably been reworked from sediments of Batesfordian age closer in-shore and redeposited in their present position. This is not unusual since the author has found *Lepidocyclina* in a phosphatic nodule on Sutherland's Cr. at an horizon well above that in which it normally occurs.

Leaf Beds near Greenbanks: From stratigraphic section No. 11 on the property known as 'Greenbanks' to as far downstream as section No. 6 (approx. 1 m. N. of Viaduct) traces of a thin arenaceous limestone or calcareous sandstone occur with poorly preserved leaf impressions. Unfortunately, poor outcrop prevents accurate determination of stratigraphic position. Broken blocks in soil have been observed from 6″ to nearly 4′ thick.

In the hand specimen, coarse well rounded quartz grains are prominent. In thin section, fine quartz grains less than 0·1 mm diameter occur in a calcitic matrix. By visual estimation in thin section, carbonate content is estimated to vary from approximately 40% to 70%.

Carbonate consists predominantly of a matrix of fine-grained clear granular calcite with quartz grains and cloudy carbonate skeletal pellets to approx. 0·1 mm. The pellets are subopaque showing only faint traces of relict organic structure. A similar feature has been noticed in the breakdown in structure of *Lithothamnion* pellets in the upper beds of the Upper Maude Limestone (bed D). In this latter case a transition can be traced from the large well preserved skeletal fragments in the lower portion of that limestone through to smaller and more structureless fragments with continued deposition and reworking of broken reef material. It seems probable that many of the subopaque pellets in this arenaceous limestone have had a similar origin and represent reworked skeletal fragments.

Fragments with any recognizable organic structure are rare. The only ones observed are small unidentifiable foraminiferal tests and ostracod shell in sample 2/10·5 from ½ m. N. of Baker's Bridge. In sample 3/9 from 'Greenbanks', in which

TABLE 15

Facies summary of Fyansford Clay and Batesford Limestone

	Facies Summary					Depositional Environment		
	Location	Lithology	Sand: clay ratio	Mineralogy (excluding clays)	Fauna	Eh	pH	Depth
Fyansford Clay	North Shore to Western Beach	calcareous clay, silty-marls, sandy limestone	high	quartz, muscovite, chloritic biotite	oysters, gasteropods	+ve	alk.	v. shallow
	Clay Point & Coghill's	calcareous clays, marls	med.	quartz, muscovite, chloritic biotite	oysters, gasteropods	+ve	alk.	shallow
	Fyansford	calcareous clays	low	quartz, muscovite, glauconite siderite	gasteropods	neut.	alk.	deeper water v. slow deposition
	Batesford	calcareous clays, marls & limestone	v. low	pyrite, glauconite, siderite	gasteropods, replacing larger forams	−ve	alk.	deepest water, poor aeration, slow deposition
Batesford Limestone	Batesford Quarry above 40′	foraminiferal limestone	low		polyzoa larger forams	+ve	alk.	shallow water
	Below 40′	polyzoal limestone	high		polyzoa mollusca etc.	+ve	alk.	shallow water

the best leaf impressions occur, there are no recognizable marine organisms. Large rounded clay pellets commonly occur to approx. 1 mm, and are usually heavily iron stained to a limonitic red. These probably represent reworked intraformational clay pellets.

In addition to quartz, chert fragments occur with traces of plagioclase and microcline. Muscovite is common with traces of pleochroic biotite and greenish brown, almost isotropic pellets, tentatively identified as oxidized glauconite.

Fossil Content: This bed is marked by a complete absence of identifiable marine fossils. Only indeterminate traces of abraded shells have been observed. Leaf impresssions, which are usually present, are invariably very poor; the only reasonable specimen containing a median rib was found near the top of the section at 'Greenbanks'. In all other places, the same characteristic arenaceous lithology can be found to contain the same indeterminate leaf impressions without any trace of marine macro-fossils which are so common throughout the remainder of the sequence.

Nearly everywhere the bed has been recorded, it is found at, or very close to, the horizon of phosphatic nodules. But whether it occurs above or below this horizon is not known. At Baker's Bridge it appears to interfinger into the clay sequence slightly below the nodule bed.

Conclusion: In the absence of accurate field relationships, the true significance of the bed is uncertain.

The complete absence of identifiable fossils and the presence of leaf impressions probably indicate a thin non-marine or near-shore environment. It is somewhat tentatively regarded as an intertonguing non-marine facies in the Fyansford Clay.

It is thought to have developed late in the history of the basin after considerable infilling had occurred. The sandy and calcareous nature of the bed in a clay sequence suggest shallower water than that in which the underlying clays were deposited. This phase may have been a forerunner of the main regression which followed shortly after the deposition of this facies. The regression is evidenced by the coarsening of detrital material with sands, gravels and phosphatic nodules slightly higher in the sequence than the leaf beds.

MOORABOOL VIADUCT SANDS

The type locality for this formation occurs at the Railway Viaduct on the Geelong-Ballarat line where it crosses the Moorabool R. 1½ m. N. of Batesford. Although the exposures here are not the best available, this locality is well known in the writings of early workers (Hall and Pritchard 1897, Mulder 1902, Singleton 1941) because of the interesting faunas which occur here and which have been identified as representing both Kalimnan and Werrikooian stages. The formation is taken to include all the arenaceous sediments stratigraphically situated above the disconformable contact with the Fyansford Clay and underlying Newer Basalt. The formation thus defined, includes a variety of minor lithological types including calcareous sands, argillaceous sands, quartzite, ferruginous sandstone and conglomerate.

Thickness and Extent: The actual thickness in the vicinity of the Viaduct is difficult to accurately determine, but is tentatively estimated at 50′-70′. For the most part, the sands to the S. and E., near Geelong, are thinner than this. In fact, the formation is very thin over the entire area, the only place in which a thickness occurs greater than that at the Viaduct, is on the Leigh R., N. of Inverleigh at Farrell's (Dennant and Mulder 1898) where 77′ of sands have been measured by the author.

Although uniformly thin, the formation covers a very wide area. Its continuity can be traced from N. of Shelford in the W., down the entire length of the Leigh R. to Inverleigh; and in the E., from N. of Sutherland's Cr. down the Moorabool Valley to the shores of Corio Bay. In fact, it can be said to cover, or at least to have covered at some time, almost the entire area affected by marine Tertiary sedimentation in this district.

Lithology: Due to the very variable nature of the lithology, study has been restricted largely to observations in the field rather than detailed laboratory work.

The discussion therefore is limited to the broader features of the lithological variations. Such variations are well represented in the vicinity of the Viaduct, but even here the detailed relationships of the sands are complex and largely obscured by later basalt flows and poor exposures.

A cross-section at the Viaduct is shown diagrammatically in Fig. 14.

From the level of the basalt plains, down the slopes of the river valley, the order of outcrop is as follows:

(a) Upper or Plains Basalt	15-20′
(b) White sands	lower contact not exposed
(c) Lower and younger basalt	to 40′
(d) Red ironstained sands, grading down to red fossiliferous calcareous sandstone and partly cemented calcareous sandstone with foraminifera	lower contact not exposed
(e) Red ferruginous sandstone on right bank below lower basalt	unknown thickness

These variations are now considered in detail, starting at the top of the section at the Viaduct and working down through the features represented on Fig. 14.

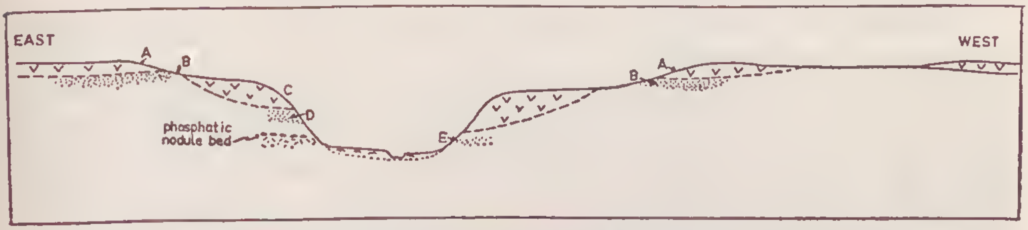


Fig. 14—Diagrammatic cross-section of sequence at the Moorabool Viaduct on the Moorabool R. For explanation, see text.

(a) The sequence is capped by a thin sheet of plains basalt to the E. and W. of the Viaduct. The base of this basalt is exposed in railway cuttings where it overlies white sands (b). Unlike the lower basalt (c) it is often strongly decomposed. It is considered to be continuous with similar basalt forming the plains to the E. and W. of the Viaduct.

(b) In railway cuttings beneath the upper basalt but well back from the present valley walls, outcrops of fine white sands occur to more than 10′ thick. These are soft, unconsolidated and somewhat variable in colour and texture from white unconsolidated sands through a mottled yellow to a red-brown limonitic concretionary sandstone. An extensive search failed to reveal any trace of fossils or calcium carbonate. Hall and Pritchard (1897) were also unsuccessful in their search for organic remains here apart from a single leaf impression which they took to indicate the 'probable fresh water nature of the deposit'. In the absence of any new evidence, these sands therefore are tentatively regarded as non-marine deposits.

(c) A second lava flow lies at a lower level than that of the basaltic plains and reaches a thickness of at least 40′ on the E. bank of the river at the railway bridge. It rests in a valley cut into Tertiary sediments down as far as the base of the sands and into the clays. When traced N. along the river's edge, the base of the flow rises until, near a track down to the river, it rests on fine red iron-stained sands. The basalt here outcrops in large fresh blocks.

This flow is regarded as younger than the plains basalt and is thought to have been extruded into a valley cut through the higher lava into underlying Tertiary sediments.

(d) Calcareous sandstone. On the E. side of the river N. of the Viaduct, a deposit of calcareous sand occurs which contains the youngest fauna recorded in the sub-basaltic sediments of the area. Mulder (1902) recorded this deposit from the two outcrops observed by the author, viz. on the track leading down to the river behind the house approx. 300 yds N. of the railway line, and also on the road cutting leading down to the river approx. ½ m. N. of the Viaduct.

The latter deposit consists of thin bedded poorly cemented calcareous sandstone grading in places to a sandy limestone. Bedding is variable but usually approximately 1″ thick with soft friable sands between harder and more calcareous bands. Pebbles of rounded quartz and slate occur near the top of the exposure in bands of calcareous conglomerate.

Quartz grains are fine to medium size and indicate medium sorting. There is an unusually large percentage of angular quartz and the association with soft slate pebbles suggests a nearby source. Chloritic biotite flakes also occur with brown polished limonitic pellets, some of which are casts of foraminifera, and may represent redeposited oxidized glauconite.

Macrofossils are rare in this outcrop but there is a foraminiferal assemblage present, as yet undetermined.

At approximately the same stratigraphic level but further to the S. along the track to the river, hard calcareous sandstone occurs with macrofossils, representatives of the fauna collected by Mulder. The outcrop at the base consists of hard reddish-yellow fine grained calcareous sandstone passing up to a yellow sandy limestone with small fossils. This in turn passes up to poorly sorted calcareous sands with gasteropods and lamellibranchs associated with coarse rounded quartz to 1″ diameter. This underlies massive fine red sands, below lower basalt.

From Mulder's collection, Tate identified 12 out of 13 species from this locality as modern living species and suggested the age to be Upper Pliocene or possibly Pleistocene. Singleton (1941) has recorded the deposit as Werrikooian.

At the top of the track and overlying the calcareous sands, a deposit of some 6-10′ thick occurs consisting of fine well-sorted heavily iron-stained and partly consolidated sands. These immediately underlie basalt and probably represent a continuation of the lower calcareous deposit from which all carbonate has been leached either before or during the extrusion of the basalt. No fossil remains have been recorded or observed in them.

(e) Red ferruginous sandstone. This is found on the W. bank of the Moorabool on the slopes immediately N. of the railway line. A residual tongue of lower basalt extends down almost to the river's edge and is underlain by the ferruginous sandstone. At this locality the Geological Survey map bears a note 'Ironstone full of fossils'. This is now somewhat misleading, since most of the material available was outwash blocks in the soil originating from below the lava residual at the W. end of the Viaduct. Much of this has apparently been removed for fossils are now rarely found.

The rock is heavily iron-stained to a dark red-brown and contains an unusually high proportion of white kaolinized felspar. This occurs to approximately 2 mm diameter associated with larger sub-rounded to sub-angular quartz. A relatively high proportion of clay present provides a suitable texture for the preservation of fossils as moulds. Carbonate has all been entirely leached from the sediment during the extensive alteration associated with the introduction of iron.

This occurrence attracted the attention of Hall and Pritchard (1897) who regarded the fauna as Miocene. Singleton, on a map of the Geelong district (1941, p. 30), shows this deposit as Kalimnan, i.e. Lower Pliocene.

The Viaduct is the only locality in the district where Werrikooian and Kalimnan faunas are both recorded in the sands. And even here, due to poor outcrop, it has not been possible to establish superposition, although the Werrikooian faunas do appear to be slightly higher than the level from which the Kalimnan ferruginous sandstone originates.

Lithologically there are significant differences between the sands containing the different faunas. The kaolinized felspar fragments, common in the Kalimnan sands are not found in the sands regarded as Werrikooian; the conglomeratic bands with slate pebbles in the latter do not appear in the ferruginous sandstones of the former. Moreover, the sands thought to be younger, still contain a high carbonate content and generally have a fresh appearance. On the other hand, the older Kalimnan sands are very strongly leached and carbonate has been replaced by limonite.

It is concluded therefore that, in this part of the Viaduct Sands at least, marine sediments of Lower Pliocene and Upper Pliocene or even Lower Pleistocene are both represented. In addition, the sands show many lithological variations, some of which are now described from other localities.

S. of Clay Point, sub-basaltic quartzite occurs as outwash blocks in the soil at the same stratigraphic level as the Viaduct Sands. Further S. near Ballarat Road, Batesford, these sub-basaltic sands contain poorly preserved molluscan moulds indicating the continuity of the marine sequence. On Ballarat Road there are two outcrops of sands in road cuttings; a higher one beneath basalt of the plains and a lower one, again overlain by basalt but almost certainly younger than the Viaduct Sands and not in any way related to them. The lower sands are regarded as deposits of the ancestral Moorabool R. which cut through the plains basalt into Tertiary sediments. Sands deposited in the river bed have been preserved by a cover of younger basalt which now appears at a lower level than that of the plains. No fossils have been found in the upper sands but, from their stratigraphical position, there is no doubt that they are continuous with the fossiliferous sandstone between Ballarat Road and the Viaduct.

In the cliff on the N. side of the Batesford quarry, a well exposed outcrop of the sands occurs. Here 28′ of sands rest with a low angular unconformity on Fyansford Clay and underlie thin lavas of the plains or upper basalt. The upper 15′ are white and poorly consolidated with 7′ of massive unbedded sands at the top. These grade down to yellow, limonitic, bedded sands 13′ thick with hard discontinuous calcareous bands (Table 16).

These bands are fossiliferous but unfortunately the age of the fauna contained in them is not known. A preliminary examination has suggested a relationship with the moulds found in the Kalimnan sandstone at the Viaduct.

Table 16

Carbonate analyses from Moorabool Viaduct Sands in cliff section below Newer Basalt, N. of Moorabool R. at Batesford quarry

Sample No.		Carbonate %
TSw5	White unconsolidated sands below Newer Basalt	nil
TSw3	Hard ferruginous bed in yellow sands 10′ above disconformity	trace
TSw2	Hard discontinuous bed in yellow sands 3′ above disconformity	62·8
TSw1	Yellow sands immediately above disconformity	65·5

In the stratigraphic sections between Batesford and Corio Bay (sections 2 and 3) no further trace of marine organism occurs in the sands. However, near North Shore, and in the railway cuttings near the International Harvester works, the formation has changed over to a coarse sandy limestone with up to 74% carbonate (see Table 14). Molluscan moulds with occasional oyster shells, indicate a marine origin for the formation to the shores of Corio Bay.

The failure to locate marine fossils at Fyansford and Coghill's is attributed to effective leaching rather than to non-marine origin at these localities.

N. of the Viaduct little is known of this formation. The arenaceous lithology can be traced to the N. side of Sutherland's Cr. but only at one locality has the continuation of the marine beds been established. This is on the S. side of the river at Moodie's (section 8B) where a molluscan fauna occurs in poorly sorted argillaceous yellow-grey sands containing coarse quartz pebbles. One mile upstream, in the vicinity of the Rowsley Fault, sub-basaltic sands in auger samples were found to be calcareous. However, northwards from here, it has not been possible to establish definite marine continuity. This may be due to the almost complete lack of satisfactory exposures of sands, apart from quartzite in the N. parts of the basin.

To the W., marine fossils have been observed in red-brown limonitic argillaceous sands at the top of an exposed sequence in a road cutting at Bruce's Cr. near Bannockburn. On the Leigh R., Dennant and Mulder (1896) record a conglomerate of 'probable Miocene age' at Shelford. This is in a position at the top of the sequence equivalent to that of the Viaduct Sands and is almost certainly a continuation of that formation. At Shelford, the ferruginous sandstone contains abundant moulds of *Pecten antiaustralis* (Dennant and Mulder op. cit.) now known as *Chlamys asperrimus antiaustralis* (Gatliff and Singleton 1930). These may be matched with an exposure on the E. side of the Leigh Valley in sands and calcareous clays near the top of the sequence (in section 111, Dennant and Mulder 1898). Here there is a sharp junction in the contact between the lower clays and marls, and the upper argillaceous sands with *Chlamys asperrimus antiaustralis*. This sharp lithological break almost certainly represents the westerly continuation of the disconformable Fyansford Clay-Viaduct Sands contact. Moreover, at the Amphitheatre, 4 m. N. of Shelford (Sec. X, Dennant and Mulder), the same transition can be observed and is here marked by a phosphatic nodule bed as at Fyansford.

A marine origin for at least the basal portion of the Viaduct Sands is therefore postulated to extend from near the Tertiary shoreline at Shelford to Corio Bay in the E.

NON-MARINE DEPOSITS OF VIADUCT SANDS

As already mentioned, Hall and Pritchard (1897) claim to have discovered evidence of possible non-marine deposition in the white and mottled sub-basaltic sands at the highest level in the railway cutting ½ m. W. of the Viaduct. These are equivalent to similar sands in the cutting on the E. near Moorabool railway station. But the extent of non-marine deposits in the Viaduct Sands is not known. The absence of marine faunas is not sufficient evidence on which to postulate a non-marine origin. Traces of carbonaceous material occur in some areas such as in the sands and quartzites beneath Newer Basalt on the banks of Sutherland's Cr., and definite leaf remains occur in a road cutting on Burnside Road near Murgheboluc in ferruginous sands. Further investigations, e.g. into variations in sorting characteristics, may yield additional evidence but, in the present study, only the upper portions of the formation which have yielded plant remains show any positive evidence of non-marine origin.

FERRUGINOUS ALTERATION

The colour changes often evident in the sands, such as in the cliff on the N. side of the river at Batesford quarry, are due to secondary leaching and oxidation. The exact age and nature of this profile development is often obscure, and may be related to either pre-basaltic or post-basaltic weathering by ground-water solutions. Judging by the variation in alteration of the fossiliferous sands at the Viaduct, the principal period of carbonate leaching with precipitation and oxidation of iron, must have preceded the deposition of the Werrikooian sands. The Kalimnan sands are extentively leached and ferruginized; the Werrikooian only slightly so.

SUB-BASALTIC QUARTZITE

In many localities where the Viaduct Sands are overlain by Newer Basalt hard siliceous bands of quartzite are developed. This is the case at Sutherland's Cr., in the railway cutting W. of the Viaduct, and on the E. valley slopes S. of Clay Point towards Ballarat Road.

In a gully N. of Sutherland's Cr. a bed of siliceous conglomerate 5′ thick overlies Maude Basalt. This passes up into, and is laterally continuous with, thin quartzite beneath Newer Basalt S. of this locality. Here, argillaceous sands and quartzites contain wood fragments suggesting a non-marine origin consistent with their lateral relationship with non-marine sands and gravels overlying Ordovician slates a short distance to the N.

FYANSFORD CLAY-VIADUCT SANDS DISCONFORMITY

The evidence for a disconformity between the Fyansford Clay and the overlying sands is provided by a small angular unconformity near Batesford, a sharp lithological change always found at the top of the clay and associated with this unconformity, the absence of faunal representatives of at least one complete stage from the sequence in the faunas so far recognized, and a very widespread association of phosphatic nodules with these features.

ANGULAR UNCONFORMITY

In the cliff section N. of the river at Batesford quarry, the Fyansford Clay and Viaduct Sands are exposed in a continuous section for some 100 yds in a NW.-SE. direction. A stratigraphic section measured at the S. end of the cliff contains 20′ more clay than a similar section at the N. end. The low south-easterly dip in the clays results in a very low angular unconformity at the contact with the Viaduct Sands which are themselves horizontal. This results in progressively younger beds being brought into contact with the sands in a south-easterly direction.

This is the only locality in which a true unconformity has been observed, and it is only evident here because of the relatively large exposure available for examination. The angle of unconformity is so small, as to be normally undetectable in the poor exposures along the Moorabool Valley. Because of the very small angle, and the inability to check this in other localities, the relationship is referred to as a 'disconformity' rather than an 'unconformity', using the terminology of Dunbar and Rogers (1957).

LITHOLOGICAL CHANGE

Associated with the disconformity, there is a very sudden change in lithology from calcareous clays to coarse sands. Not only is this present at Batesford, but it is found wherever the sand-clay contact is exposed. It is found at Shelford in the W., where the lithological change is accompanied by phosphatic nodules and important

TABLE 17
Facies Summary—Viaduct Sands

FACIES					ENVIRONMENT OF DEPOSITION
Locality	Composition	Grain Types	Faunas	Secondary Alteration	
Sutherland's Cr.	quartz	poorly sorted angular	carbonaceous material	silicification with opaline cement	non-marine shallow water
Viaduct in railway cutting (*b*)	quartz	medium sorting, sub-rounded	(?) leaf remains	ferruginous mottling	(?) non-marine shallow water
Moorabool River Valley (*d*)	quartz, calcite, slate pebbles	medium sorting, angular	Werrikooian, forams, lamellibranchs		marine shallow water
Moorabool River Valley (*e*)	quartz, decomposed felspar, limonite	medium sorting, angular	Kalimnan gastropods	carbonate leaching, and ferruginization	marine shallow water
Batesford Quarry	quartz, calcite, limonite	medium sorting, sub-rounded	oysters, lamellibranchs, gasteropods	carbonate leaching, and ferruginization	marine shallow water
Corio Bay	quartz, calcite	medium sorting, well rounded	oysters, lamellibranchs	leaching of carbonate	marine shallow water

faunal changes, to as far as Corio Bay in the E. where almost exactly the same criteria occur. At a great number of localities between, the same lithological changes are evident.

FAUNAL BREAK

Of all the faunas so far recorded from the sequence in the Geelong area, none has yet been assigned a Cheltenhamian age. On the other hand, Kalimnan, Bairnsdalian and Balcombian stages have been reported. The apparent break in the faunal sequence corresponds precisely to the disconformity evident in the field, and since definite erosion is known to have occurred along the disconformity, some faunal gaps would be expected. However, because of the unsatisfactory state of Upper Tertiary stages and the lack of diagnostic faunas, it is impossible to estimate the magnitude of the gap represented by the disconformity.

At Beaumaris, some 40 m. NE., a similar phosphatic nodule bed is associated with a similar lithological change from clays to sands and occurs at the base of the type section of the Cheltenhamian. The nodule bed and associated disconformity may therefore represent a diachronous horizon being a different age in different places and cutting across time boundaries, so that while erosion was taking place in one environment, deposition was occurring in another, probably further off-shore.

PHOSPHATIC NODULES

These have been recorded and described by Coulson (1932) and Keble (1932) in the vicinity of Geelong. In the course of the present work, nodules have been found over a very wide area from the Amphitheatre, N. of Shelford in the NW., to Murgheboluc in the SW., and from Sutherland's Cr. in the N., to the shores of Corio Bay in the E. When found, they are always associated with the lithological change which characterizes the disconformity, although nodules are not present at all localities at which the disconformity is represented. They do not form a continuous deposit, but tend to be localized in thin bands, usually less than 6″ thick. They are not present, e.g. in the cliff N. of Batesford quarry where the angular unconformity exists. But they do occur in equivalent positions in the sections measured on either side of this cliff, i.e. at Clay Point, Coghill's and Fyansford road cutting.

They are essentially associated with the disconformity both in origin and occurrence and, in places where outcrop is poor, they may be found as outwash material in soil on the valley slopes providing evidence for continuity of the disconformity.

Distinction Between 'Nodules' and 'Concretions': To avoid confusion in the use of these terms when referring to phosphorites, it is proposed to use them only in the sense of Pettijohn (1957, p. 200, 203). The term 'nodule' refers to 'irregular tuberous bodies of mineral matter unlike that of the host rock in which they occur'. A concretion on the other hand is 'an accumulation of mineral matter in the pores of the sediment about a nucleus or centre'.

The phosphatic nodules are separate entities from the sedimentary matrix in which they are located. At Geelong, and neighbouring localities, as recorded by Coulson, they often possess a dark brown exterior and highly polished surfaces. Some bear distinctive surface marking such as pholad borings and polyzoan incrustations indicative of a long period on the sea floor before final burial.

The concretions, however, grade outwards into the containing sediment and are not separated from it by a sharp boundary. They lack polished surfaces and may occur in a variety of shapes, many of which are found to cut across bedding planes in the sediment. This provides conclusive evidence that they have formed after deposition during diagenesis, and not as a syngenetic deposit on the sea floor at the water-sediment interface. They will always be found to contain a fauna identical with that of the sediment in which they occur.

Coulson (op. cit.) has recorded the widespread occurrence of concretionary phosphates from Thompson's Cr., Moriac, Torquay, Waurn Ponds and Western Beach. In addition, a prominent occurrence is found at the Amphitheatre, on the Leigh R., N. of Shelford. Here limestones and silty clays pass up to 30′ of clays which, in turn, are overlain disconformably by sands equivalent to the Viaduct Sands. The limestones are limonitic and weathered in outcrop but, on the weathered surface, brown resistant phosphatic concretions often protrude. These occur in a variety of shapes but are usually rounded, elongate or torpedo-shaped. The interior is a dark brown to black, grading outwards to a lighter brown and eventually merging into the surrounding sediment. The dark interior of the concretions reacts strongly to a phosphate test.

It would seem then that such diagenetic concretions have attained a widespread, if somewhat sporadic distribution throughout the Miocene sequence of Western Victoria, at least from Shelford to Torquay.

Origin of Nodules:

Original Theory of Coulson and Keble: Keble (1932) made a study of the faunas associated with the nodules on the disconformity and he came to the conclusion that the enclosed faunas were older than the faunas of the enclosing sediment. The nodules were therefore considered to be *remanié* in their origin. Keble recognized the affinities of the enclosed faunas with that of the older Janjukian limestones as at Waurn Ponds in which concretionary phosphate occurs. But to account for the abundance of enclosed crabs, both Keble and Coulson have invoked two periods of formation as summarized by Coulson (p. 126)—

'(a) Uplift and emergence of the Miocene limestone.
(b) Erosion of post-Miocene valleys.
(c) Slow subsidence and invasion of the sea.
(d) Gradual uplift, complete emergence.
(e) Deposition of Pliocene sands.
(f) Erosion.
(g) Newer Basalt flows.'

In the course of the present investigation, the views of Coulson and Keble that nodules are *remanié* in origin have been confirmed. However, the writer disagrees with the contention of these workers that two stages of formation are necessary. There appears to be no adequate evidence that the erosion which gave rise to the disconformity took place under sub-aerial conditions as postulated by Coulson. He has claimed the existence of valleys in which the nodules have accumulated. But these may alternatively be regarded as shallow depressions on the sea floor. The author believes that erosion took place under sub-marine conditions due to reduction of base level at the commencement of marine regression.

Marine Miocene clays pass up across a sharp contact to younger Upper Tertiary marine sands. There is no evidence of terrestrial deposits separating the two. The removal of portion of the sequence below the disconformity (evident in the existence of the small angular unconformity at Batesford) is thought to be due to the marked shallowing of the sea bringing the fine clays and marls into the zone of wave activity.

In this shallow water zone, sediments of a much coarser grain size than clays would have been at equilibrium with the strong currents. Unstable fines were removed and coarse-grained sediments deposited. This has resulted in the sharp lithological transition at the contact of Fyansford Clay and Viaduct Sands.

The facies change evident between these two formations is attributed therefore to the change in conditions of deposition which occurred at the commencement of regression. This was probably initiated due to uplift of the Central Victorian region. Uplift resulted in a series of events including shallowing of the sea, submarine erosion of sediments deposited earlier in deeper water, increase in the rate of erosion on land with corresponding increase in the rate of supply of coarse terrigenous material to the basin. This eventually resulted in the retreat of the sea from the entire area.

OTHER THEORIES: There appear to be three possible mechanisms by which the nodules may have originated:

(1) By formation essentially in nodular shape on the sea floor.
(2) By derivation from phosphatic concretions in older sediments (*remainié* origin).
(3) By the breaking up of a slabby bed of primary phosphorite formed on the sea floor.

(1) Formation as nodules on the sea floor:

This explanation has been put forward by Emery, Dietz and others in a series of papers (1942, 45, 50, 52) to explain nodules on the present sea floor off the coast of California. However, it is inadequate in the case of the Geelong nodules for the following reasons:

(a) The shape of the nodules is such that they show definite evidence of abrasion rather than accumulation and growth *in situ*. Mammillary or typical growth surfaces are absent and on the outside of the nodules outlines of contained shells are truncated by abrasion.

(b) The fossils found in some nodules are older than the sediments in which they occur. This is born out by Keble's investigation (1932) and the author's observations of *Lepidocyclina*-bearing phosphorite on the disconformity well above the normal Batesfordian horizon of that genus (Pl. XVIII, fig. 3). It may be argued that these fossils have eroded out of older rocks and have been recemented by phosphate on the sea floor. This was the explanation offered by the Californian workers to explain nodules containing almost exclusively Miocene faunas on the sea floor off California. In such circumstances, however, most nodules would be expected to contain a mixed fauna. But these are rarely recorded. In a table recording occurrences of modern phosphorite, Emery and Shepard (1945) record 1,112 samples containing Miocene foraminifera whilst only 15 contained a Pliocene or Quaternary fauna, and then in matrix only. Whilst nodules containing exclusively Miocene, Pliocene or Quaternary faunas are known to occur, evidence of nodules containing faunas of mixed age is rarely recorded.

Moreover, the *Lepidocyclina* tests themselves, in a nodule at Sutherland's Cr., show no sign of abrasion as do those occurring in the marly facies of the Fyansford Clay near Lethbridge. In this latter case, the actual tests have been eroded, abraded and redeposited but, in the former, they have been protected in the entire body of phosphatized Batesfordian sediment which has been abraded and redeposited.

It is often claimed that phosphates, like glauconite, indicate environments of non-deposition. This is partly true, but it is not considered adequate to explain the occurrence in the Geelong area where there is evidence, not only of non-deposition, but of active erosion. Moreover, an environment of non-deposition in shallow water and a relatively warm climate which existed at the time of the development of the nodule bed, would be exactly the environment in which benthonic mollusca, polyzoa and other organisms would flourish, resulting in the development of a calcareous facies. If such conditions persisted, a considerable thickness of limestone would be expected to occur. It is conditions similar to these which are thought to have resulted in the accumulation of the Bairnsdale Limestone, when little or no terrigenous material was being supplied to the Gippsland basin (R. W. T. Wilkins pers. comm.).

The absence of a well defined calcareous facies specifically associated with the disconformity and nodule bed therefore suggests that conditions of non-deposition were not those responsible for the phosphorite.

(2) Derivation from older sediment—*remanié* origin:

The author is in agreement with Coulson and Keble that there is definite evidence to substantiate a *remanié* origin for a large part, if not all, of the nodules at Geelong.

There is ample concretionary phosphate in some horizons of the underlying sediment which, if eroded, would develop into nodular phosphorites. These would contain a fauna older than the horizon on which the nodules now occur, as observed by Keble and the author at Geelong, and by workers studying nodular phosphorites off California.

The phosphorite with *Lepidocyclina* above is regarded as a fragment of sediment of Batesfordian age cemented by phosphate, which has been reworked and redeposited by strong currents. Further evidence of reworking is found associated with nodules at Beaumaris. Here *remanié* tests of *Lepidocyclina* are known to occur in the sands for several feet above the nodule horizon which is separated from sediments of true Batesfordian age by an unknown thickness of younger clays.

It is concluded therefore that reworking of older sediments has occurred at Geelong and possibly at Beaumaris and, in the former case at least, phosphatic concretions are known to be present in the underlying rocks in many localities, and these have been eroded out to form lag deposits in the shallow water environment.

(3) Breaking up of a phosphorite bed formed on the sea floor:

Coulson and Keble, in addition to postulating a *remanié* origin, invoked a second period of formation involving two marine cycles with a period of complete emergence between. In the second of these, they have suggested the formation of an 'intermediate bed' of phosphorite.

It is well known that phosphate can be precipitated from sea water and is found to coat gravels and pebbles of other rocks, e.g. basalt, in some examples of modern sediments. Moreover, Emery (1960) has recorded slabby phosphorite in some samples from the modern ocean floor. These often contain Quaternary or Pliocene faunas and have undoubtedly formed *in situ* by the precipitation of primary or syngenetic phosphate. However, in such examples, the following criteria may be expected to occur:

(a) When nodules of *remanié* origin are present, they will sometimes be enclosed in a matrix of younger phosphorite. This, when eroded would result in a 'nodule-in-nodule' structure or slabby phosphorite containing older cemented nodules. This does occur in the Californian examples but has never been recorded nor observed by the writer in the Geelong phosphorites.

(b) Faunas of mixed age would be found in such examples, the fauna of the matrix being younger than that of the nodules which it enclosed.

The intermediate bed was proposed by Coulson and Keble to account for the abundance of *Ommatocarcinus corioensis* in the nodules at Geelong. The stratigraphic range of the genus is not yet accurately known. At Shelford and Torquay, the author has found crab remains in phosphatic concretions *in situ* in sediment of Lower Tertiary age and there seems no reason why such concretions could not give rise to *remanié* nodules with crab remains similar to those noted by Keble.

Conclusion: The evidence for an intermediate bed of primary or syngenetic phosphorite as an origin for some of the nodules is a possibility, but lacks any positive evidence in the Geelong district. On the other hand, there is positive evidence that at least some, if not all the nodules present, have been derived from the erosion of older sediments containing phosphatic concretions. There is no evidence that complete emergence occurred prior to the development of an intermediate bed as suggested by other workers. The disconformity and nodule bed forms rather an important horizon representing a specific phase in a single marine cycle of deposition. The sequence of events involved is summarized below and represented diagrammatically in Fig. 15.

During early Tertiary sedimentation, sediments were deposited which contained fine-grained chemically or organically derived phosphate, such as that found in the wide occurrence of phosphatic shales, or in the Cretaceous Chalk of Great Britain where it is associated with glauconite.

Large amounts of biochemically derived phosphate were associated with abundant Miocene faunas.

After burial, and during consolidation of the sediment, the phosphate was relatively quickly mobilized and concentrated around a phosphatic nucleus in the sediment, thus forming a phosphatic concretion. In the Lower Tertiary sediments at the Amphitheatre, Shelford, crab remains and vertical burrows have been observed to form the nuclei of some of these concretions.

Phosphate deposition diminished during the deposition of the clay sequence for it occurs predominantly in the more calcareous beds.

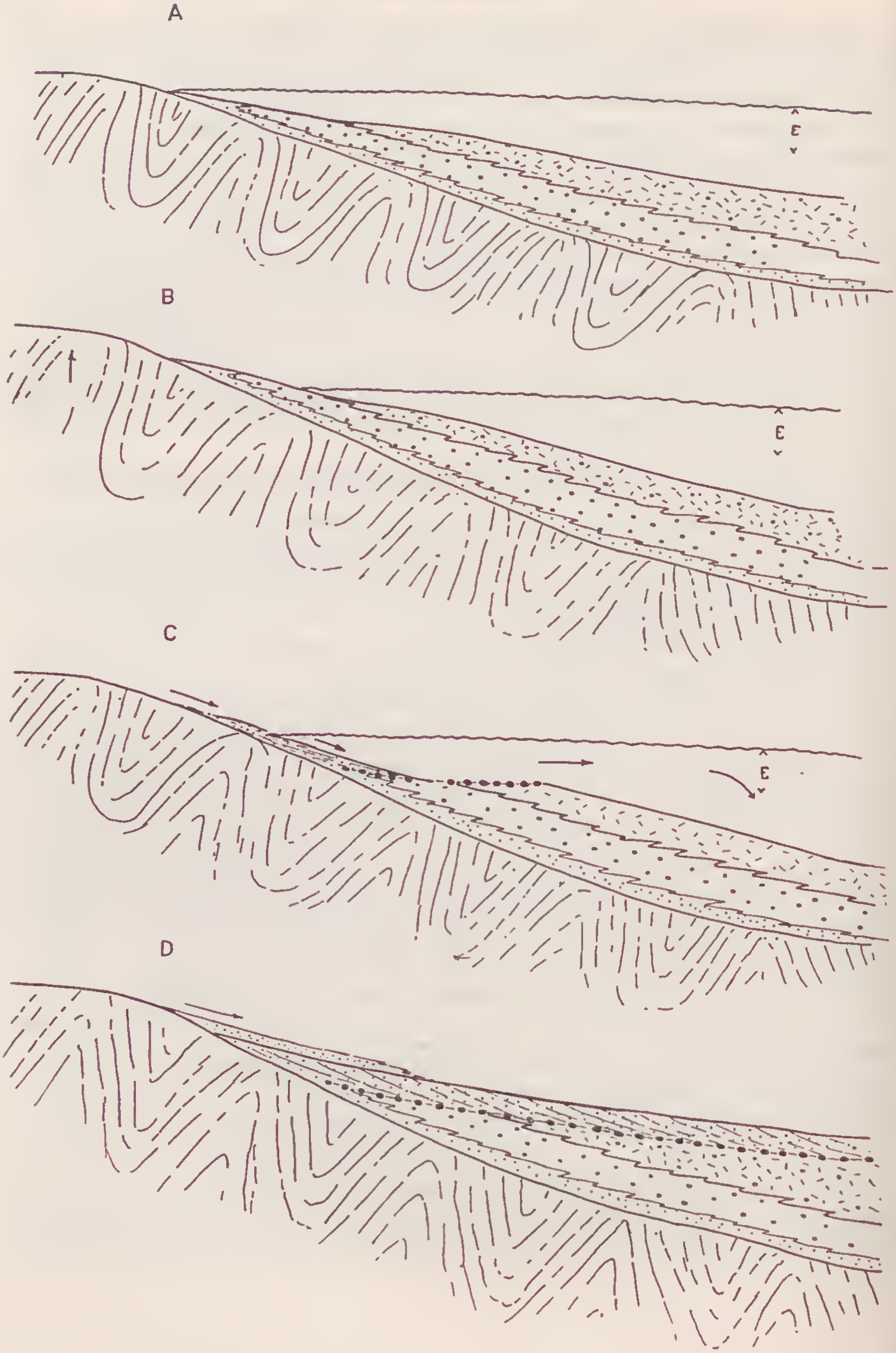
After deposition of the clays, the regressive stage commenced due to late Tertiary uplift and with it there was a marked shallowing of the sea, bringing older and partly consolidated sediments into the zone of wave activity, thus subjecting them to submarine erosion. Submarine erosion removed relatively large quantities of older sediment forming such features as the widespread disconformity with a small angular unconformity at Batesford. As the fine material was winnowed out to be redeposited elsewhere off-shore, the now consolidated phosphatic concretions remained behind as a lag deposit being corroded and rolled on the sea floor during the long period of basal reduction under a slowly shallowing sea. Associated with such nodules, other hydraulically equivalent pebbles or cobbles were redistributed, such as the quartz pebbles which occasionally are to be found with the nodules, e.g. in the section at Coghill's.

The final stage resulted in the deposition of the very shallow water sands which overlie the nodule bed and represent the final event in the recession of the Tertiary sea in Pliocene time.

While there are difficulties in this explanation, it is held that it best explains the observed facts, as now known.

NON-MARINE SANDS AND GRAVELS OF MAUDE, STEIGLITZ AND ANAKIE

The occurrences of gravels at Maude and their relationships to the non-marine gravels on the Steiglitz plateau to the N. of Maude have been summarized by Harris and Thomas (1949).


A
E
B
E
C
E
D

They have recognized three series of gravels near Maude:

(1) Siliceous conglomerates which rest on bedrock and are claimed to be older than the sands and gravels of the Lower Maude Formation.
(2) Unconsolidated sands and gravels of the Lower Maude Formation with similar lateral equivalents in Sutherland's Cr.
(3) Sands and gravels which unconformably (or disconformably) overlie the marine fossiliferous beds on the Upper Maude limestone and clay and directly underlie Newer Basalt.

The writer is in substantial agreement with the suggestions of Harris and Thomas but would make one amendment.

Apart from secondary silicification, there appears to be little valid evidence for distinguishing the siliceous conglomerate of (1) from the sands and gravels of (2). The former are continuous with the Sutherland's Creek Sands which themselves are often prominently silicified. They lie on bedrock just as the siliceous conglomerate.

The gravels are then reduced to two horizons, an older and a younger series which interfinger in the marine sequence and can be traced northwards onto peneplained Ordovician slates.

On some maps of the Geological Survey, e.g. Quarter Sheet 19 SW., gravels outside the limits of marine sedimentation are often differentiated into Miocene and Pliocene and are represented as such in different colours. Sands and gravels of Upper Tertiary and Lower Tertiary age are present in the marine sequence and these can be traced for a short distance inland into non-marine sediments. The criteria used to recognize terrestrial sands and gravels are two:

(1) All sediments considered to lie outside the maximum limits of the marine transgression.
(2) Those sands or gravels which contain ferruginized fragments of wood, as recorded by Wilkinson and Murray on Quarter Sheet 19 SW., and confirmed by the author.

Gravels of various ages are known to be represented and are still accumulating in the present erosive cycle as alluvial deposits, some of which contained payable auriferous deposits. But differentiation between the various Tertiary sands and gravels away from the shoreline presents many difficulties, which raise doubts about validity of the 'Miocene' and 'Pliocene' ages assigned to them by the early Geological Survey workers.

Fig. 15—Suggested stages in the devolpment of the phosphatic nodule bed and disconformity between the Moorabool Viaduct Sands and Fyansford Clay.

A. Clays, limestone and marginal sands deposited in neritic sea lens out against rising Palaeozoic bedrock. Phosphate material, either chemically or biochemically derived is mobilized during diagenesis and concentrated around a suitable nucleus forming a hard phosphatic concretion.

B. Reduction in sea level during regression brings limestone containing phosphatic concretions into the zone of submarine erosion (E).

C. Some clays and limestone are eroded leaving concretions as abraded and rolled residual deposits, sometimes associated with quartz gravels. These in turn are covered by younger shallow-water sands. Eroded sediments may be deposited in deeper off-shore environments where continuous deposition may be expected equivalent to the erosion break closer in-shore. A disconformity of this nature is therefore considered to be diachronous.

D. After final retreat of the sea from the area, the disconformity and nodule bed now correspond to a sharp lithological change and, at Batesford, to a low angular unconformity.

OLDER GRAVELS

These occur at various localities N. of the Tertiary shoreline. The most extensive deposits of coarse gravels occur close to the N. limit of Tertiary marine sediments on slopes dissected by recent drainage 3 m. NW. of Maude. At this locality, gravels are extracted for road metal over a lateral extent of some 100 acres and reach a maximum thickness of at least 150′. They can be traced to the N. across Sutherland's Cr. thinning out on the rising Ordovician slates and underlying remnant outliers of Maude Basalt. They thin out to the W. and to the E., passing laterally into the finer Sutherland's Creek Sands.

The gravels consist of a basal conglomerate of large boulders of Ordovician reef quartz and sandstone with smaller fragments of slate. Boulders to 2′ diameter are common. The basal 6′ of the deposit is often cemented into a very hard conglomerate with a siliceous and ferruginous cement. Vertically, this passes up to non-cemented, very coarse, poorly sorted and sub-rounded gravels with few boulders and eventually to finer gravels, quartz grits and clays towards the top of the sequence. The rock types represented appear to be derived entirely from Palaeozoic rocks.

The gravels are continuous to the S. with the Lower Maude Gravels which pass under the Lower Maude Limestone. Since the latter is considered to be Janjukian, the gravels are themselves Janjukian or older. N. of Sutherland's Cr. they underlie Maude Basalt which serves to distinguish them from the younger sands and gravels which overlie the basalt at other localities.

ORIGIN: The mechanism by which these older gravels were accumulated is not known. They were possibly concentrated around the margins of the Tertiary basin by southerly flowing streams in early Tertiary time. But whatever mechanism was involved considerable energy was required to distribute the large rounded boulders which occur at the base of the sequence.

YOUNGER SANDS AND GRAVELS

In a gully running N. from Sutherland's Cr., quartzite and siliceous conglomerate 5′ thick lies between Maude Basalt and Newer Basalt in a stratigraphic position equivalent to the Moorabool Viaduct Sands. This marks the N. limit of Tertiary marine sediments and the quartzite here is considered to be at least in part marine in origin, although palaeontological evidence is lacking. Harris and Thomas (1949) refer to the strongly unconformable relationship with the underlying marine clays and limestone. This represents the Fyansford Clay-Viaduct Sands disconformity which can be traced inland to Sutherland's Cr.

Further to the N., extensive deposits of sands occur which are well outside the limits of marine sedimentation. These are prominently developed at many localities on the Steiglitz Plateau, e.g. in the road cutting up the scarp at Anakie and along Boardman's Track. Other deposits occur marginal to the Tertiary shoreline and are tentatively regarded as non-marine, such as that which overlies granite on the E. branch of Sutherland's Cr.

On Anakie Road, medium to fine grained sands 28′ thick unconformably overlie Ordovician sandstones and slates. The basal 2′ of the deposit contains some pebbles and boulders of Ordovician sediment but quickly passes to well bedded and often poorly sorted sands cemented in a strongly ferruginized and highly limonitic matrix. The entire deposit is red-brown with poorly developed mottling near the surface.

Further S. near the fault scarp W. of O'Neil's Lane, similar strongly ferruginized sandstone passes down to reddish-yellow partly cemented sands, then to a mottled zone which overlies white sands and gravels. The total thickness here is approximately 35′ but the thickness of individual zones is difficult to estimate.

Sands similar to either of these two occurrences are common at many places on the undissected summits of the Steiglitz Plateau and form red soils, often with prominent mottling in the B horizon and typical lateritic appearance.

E. of the Rowsley Fault in a very good exposure on the East Branch of Sutherland's Cr., very strongly ferruginized sands occur to a depth of more than 40′ (a detailed description of this profile will be given elsewhere).

The sands at this locality are unfossiliferous and are tentatively regarded as equivalents of the ferruginous sands on the Steiglitz Plateau. Their nodular character appears similar to an advanced stage of the mottling present in the sands on the plateau to the W.

AGE AND ORIGIN: The relationship of these sands to marine deposits of known age further to the S. is not clear. At a locality N. of Sutherland's Cr. (264,204) ferruginous sandstone occurs between Maude Basalt and Newer Basalt. It contains limonitically replaced wood fragments and is almost certainly terrestrial in origin. Its position between the basalts would make it stratigraphically equivalent to the Moorabool Viaduct Sands or arenaceous equivalents of the Fyansford Clay.

Further N., Maude Basalt is absent but ferruginous sandstone continues to Anakie and beyond. It therefore appears that the major portion of the ferruginous sands are younger than the Maude Basalt and would be Upper Tertiary rather than Lower Tertiary in age. However, lithological similarity is considered insufficient evidence to establish synchronous relationships with the Moorabool Viaduct Sands in the marine sequence. Some may be much older than Pliocene and in places there may have been slow but continuous non-marine accumulation since the deposition of the thick Lower Tertiary gravels near Steiglitz. In the absence of Maude Basalt which acts as a marker separating the two, it is impossible to say with any certainty what age the sands or gravels may represent N. of the Tertiary shoreline.

It is concluded therefore, that the sands and gravels on and near the Steiglitz Plateau represent accumulations which may have been taking place throughout the Tertiary, as well as recent deposits which occur on the slopes and valley floors of present streams. Reworking of some of the Lower Tertiary sands and gravels, however, is thought to have resulted in redeposition of fine sands in late Tertiary time followed by extensive ferruginization. In most cases there is insufficient evidence to differentiate between Lower Tertiary and Upper Tertiary terrigenous sediments. The practice of early workers of the Geological Survey in differentiating terrigenous sediments into gravels of Miocene and Pliocene age, sometimes directly overlying each other, as on the fault scarp N. of Sutherland's Cr., is considered therefore to be invalid except where separated from each other by Maude Basalt. And even then, the closest age determination that may be validly assigned to them is Lower Tertiary and Upper Tertiary.

Detailed Stratigraphic Relationships and Time-Rock Correlation

The relationships between rock units recognized in the sequence are illustrated in Fig. 2, 3, 13, 16 and 19.

The oldest beds exposed are those in the N. near the limits of Tertiary transgression, i.e. beds of the Lower Maude Formation. Earlier workers have reached general agreement that the Lower Maude Limestone is the same age as the lower beds at Spring Cr., Torquay, the type locality of the Janjukian stage. If the Oligo-Miocene transgression advanced from the SW., the basal marine deposits of the

Torquay sequence (located approximately 40 m. S. of Maude) should be older than the basal beds at Maude. There appears to be a significant absence of transgressive onlap normally associated with a slow transgression. It would seem then, that initial transgression occurred rapidly, depositing beds of approximately the same age at Maude and at Torquay, 40 m. to the S. In this case, there should be equivalent Janjukian deposits between these two localities. Singleton (1941) suggested a Janjukian age for the Waurn Ponds limestones; Hall and Pritchard (1895) suggested a similar age for the limestone at Belmont on the S. side of the Barwon near Geelong. However, no equivalents of the Lower Maude Limestone have been recognized in the sequence near Geelong N. of the Barwon R.

This raises the question whether marine deposition occurred N. of the Barrabool Hills in Janjukian time.

Sediments of Janjukian age may occur in the basal portions of the Batesford Limestone, which have not yet been examined palaeontologically. The uppermost 40′ of limestone is of Batesfordian age as defined by Singleton (1941) on the occurrence of *Lepidocyclina*, and this genus persists for 10′ into the overlying clays. The Batesfordian stage then does not correspond to the lithological or formation boundary. The limestone at the base of the present quarry is pre-Batesfordian, and does not contain *Lepidocyclina*. It is regarded as Longfordian by Carter (1963) and it is held that the limestone which underlies it will prove to be Longfordian (in the sense of Carter 1959) or Janjukian (see Fig. 16).

Limestone is known to occur on one of the highest points of the Barrabool Hills overlying diabase W. of Ceres (Coulson 1960), and there is little doubt that the sea covered the Barrabool Hills in early Tertiary time and that the principal period of Barrabool uplift is post-Janjukian. Therefore, Janjukian sediments probably exist in the deeper off-shore areas between the Dog Rocks and the present course of the Barwon R., and possibly at depth in other localities to the N. not yet known.

SIGNIFICANCE OF MAUDE BASALT

All available evidence suggests that the basalt was extruded under mainly subaerial conditions on top of the Lower Maude marine beds.

To account for this there must have been a slight regression towards the end of Janjukian deposition, corresponding to the top of the Lower Maude Limestone. This could have been caused by slight uplift of the N. area along an E.-W. axis near Maude which could also have coincided with, or even have triggered off, local volcanic activity. The absence of an erosional break between the Lower Maude Limestone and the base of the basalt, suggests that regression and lava extrusion followed each other very closely without any significant sub-aerial erosion.

The presence of pillow lavas near Russell's Bridge, suggests that the new shoreline may have been situated in this vicinity.

There followed then, a period of minor transgression at Maude with the deposition of littoral deposits on the eroded surface of the basalt. The extent of erosion and the nature of the Upper Maude Limestone indicate relatively slow deposition in an advancing sea. The overall thickness of basalt (approx. 100′) would necessitate a deepening in the adjacent waters of a similar amount before the next transgressive phase could deposit the limestones at the new shoreline N. of Maude school. This minor transgression, and the disconformable break associated with it, are represented at Batesford by apparently continuous deposition. Attempts to locate a corresponding break in the deposition of the limestone at Batesford have proved unsuccessful.

The presence of *Lepidocyclina* near the shoreline at Maude school provides confirmatory evidence for the correlation of the Upper Maude Limestone with the upper portion of the Batesford Limestone, or true Batesfordian. It will be recalled that evidence of slow deepening has been suggested in the change of detrital material (disappearance of granitic detritus) occurring in the upper part of the Batesford Limestone becoming prominent with the entry of *Lepidocyclina*. It is believed that this correlates with the transgressive advance of shoreline from Russell's Bridge to Maude during which time the Upper Maude Limestone was deposited, equivalent to the upper 40′ of the Batesford Limestone.

AGE OF UPPER MAUDE LIMESTONE-BASALT DISCONFORMITY

The presence of a strongly eroded surface between the Upper Maude Limestone and Maude Basalt associated with minor regression and transgression indicates that portion of the sequence at Maude is missing.

If the Lower Maude Limestone is Janjukian and the Upper Maude Limestone is Batesfordian, then the break in the sequence must be equivalent to Longfordian

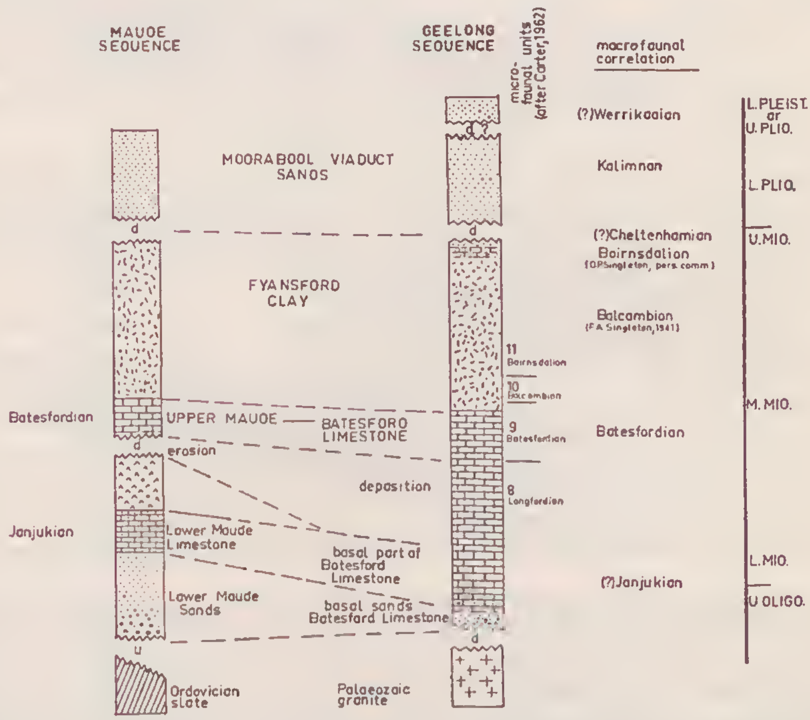


Fig. 16—Stratigraphic correlation diagram showing the rock and suggested time-rock correlation between the sequences at Maude and Geelong. The age of the disconformity between the Moorabool Viaduct Sands and Fyansford Clay is thought to be older near shoreline in the N. than at Geelong. The overlap between the macrofaunal and microfaunal age determinations of the Fyansford Clay is largely due to inherent difficulties in correlating by stages erected from completely different and unrelated sequences as in the case of the Batesfordian and Balcombian as defined by Singleton (1941) and Bairnsdalian as defined by Crespin (1943) and later modified by Carter (1959). Carter (1963) has recently correlated his faunal units with the Balcombian and Batesfordian type sections. But since F. A. Singleton's determination, no further macrofaunal evidence from the area has been published.

as defined by Carter (1959), i.e. the Longfordian stage is apparently represented by the Maude Basalt and the erosion surface at the base of the Upper Maude Limestone.

In the Batesford quarry, Carter (1963) has recognized Faunal Unit 8 (Longfordian) from the quarry floor and well above the basal portion of the limestone. Faunal Units 6 and 7 may be present below the quarry floor.

It is concluded therefore that the floor of the present quarry is approximately equivalent to the erosional break at the top of the Maude Basalt and the base of the Upper Maude Limestone and that, while non-deposition and erosion were occurring at Maude, continuous deposition occurred at Batesford.

PHASE OF MAXIMUM TRANSGRESSION AND DEEPER WATER SEDIMENTS

The principal period of maximum transgression is represented by a facies change at the top of the Upper Maude and Batesford limestones. This is predominantly a lithological change from limestone to clay with associated faunal changes from clear to muddy water forms. At Batesford a change from an oxidizing to a reducing environment is indicated by the appearance of pyritic clays. During this period the Dog Rocks, which had been only partly submerged in Batesfordian time, was now completely covered by the deeper water, and granitic detritus ceased to be an important factor in the supply of detritus to the adjacent environments.

A difficulty arises in the new position of shoreline near Maude. There is no evidence that even in this period, the shoreline extended much further inland onto Ordovician slates N. of Maude than it did during the shallow water deposition of the underlying limestones. In all probability it must have transgressed for at least a short distance N. of the Lower Maude Formation and Upper Maude Limestone limits, but no evidence of this now remains.

The mechanism postulated to explain deepening is a continuation of the earlier movements which controlled the shoreline near Maude in Janjukian and Batesfordian time, i.e. a continuation of movement along a warp running E.-W. N. of the Maude school. This warp appears to have been active from pre-Janjukian to Recent time for it still exerts a strong control on the geomorphology of the area.

If the predominant movement in Batesfordian-Balcombian time is thought of as a downwarp of the basin along the margin, rather than upwarp to the N., then this accounts for continued deepening without significant onlap, and without an influx of coarse detritus from the N. This mechanism is illustrated diagrammatically in Fig. 17.

The change in the levels of Ordovician basement from Bannockburn, where it is recorded in a Mines Dept bore at approximately 400′ below sea level, to N. of Steiglitz where it forms a plateau at an elevation of 1,200′, represents a change in level of 1,600′ over a distance of less than 12 m. While some of this may be due to pre-Tertiary erosion, the greater part is certainly due to tectonic movements in Tertiary and post-Tertiary time.

Post-Janjukian and pre-Pliocene sediments (limestone, marl and clay) contain relatively small amounts of coarse detrital material suggesting low relief on the Ordovician plateau to the N., and little relative upwarp of this area. The predominance of clays to the top of the sequence suggests that elluviation continued on land over a long period throughout the Miocene, probably as a result of low topographic relief and relatively deep weathering. Gravels and coarse quartz sands remained on the land surface until Upper Miocene and later tectonics initiated active erosion. The gravels were then reworked and concentrated by the rejuvenated drainage system which carried large amounts of coarse material out to the basin.

BATESFORDIAN-BALCOMBIAN RELATIONSHIPS

As indicated previously, the Batesford Limestone represents a typically transgressive facies overlapping onto Dog Rocks granite. Its formation boundaries are diachronous as illustrated in Fig. 13. To some extent therefore, the upper part of the

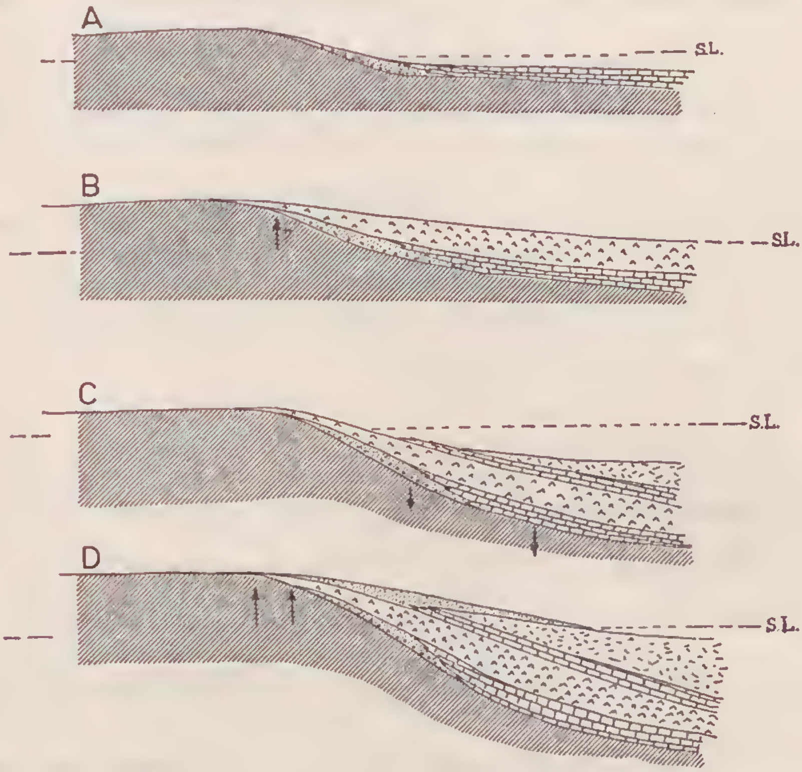


Fig. 17—Diagrammatic N.-S. cross-section to illustrate the movements postulated along E.-W. flexure between Maude and Steiglitz controlling the location of the Tertiary shoreline despite variations in depth of water.

A. Early Tertiary movement is regarded as a slight downwarp of the basin allowing the shoreline to advance to N. of Maude and maintaining low topographic relief to the N.

B. Slight regional uplift was probably associated with the extrusion of the Maude Basalt enabling it to be extruded under sub-aerial conditions S. to near Russell's Bridge.

C. Slight downwarp of the basin (or eustatic rise in sea level) resulted in transgressive advance across the Maude Basalt depositing Upper Maude Limestone with later deposition of the deeper-water clay facies, but there is no evidence of transgressive onlap beyond the position of the Lower Tertiary shoreline on to Palaeozoic bedrock.

D. In Late Tertiary, regional upwarp of the area resulted in shallowing seas and gradual retreat. Drainage was rejuvenated on the land mass to the N. and abundant coarse to fine-grained sands were supplied to the environment.

Batesford Limestone and the lower part of the Fyansford Clay are lateral equivalents. This raises the difficulty of recognizing the Batesfordian stage in a non-calcareous or clay facies. The benthonic foraminifera used in the original definition of this stage (Singleton 1941) are subject to very strong facies control, as indicated by a marked variation in occurrence of *Lepidocyclina* at different locations on the same stratigraphic horizon.

Its occurrence appears to be restricted to near-shore calcareous facies similar to that described from around the Dog Rocks. Its abundance decreases laterally away from the ancient shoreline in inverse proportion to the percentage clay in the sediment.

In a bore on the S. side of the Dog Rocks where the Batesfordian stage is represented by a silt-clay facies, *Lepidocyclina* tests were rare in contrast to their abundance in the limestone in the upper part of the quarry. If the beds of Batesfordian age could be traced far enough to an entirely clay facies, *Lepidocyclina* would probably disappear altogether.

The strong environmental control therefore limits its use as a zone fossil and other means must be used to differentiate the Batesfordian stage in an argillaceous facies where benthonic foraminifera may be absent.

It is significant perhaps that all recorded occurrences of *Lepidocyclina* in Victoria (excluding *remanié* tests) have been in littoral or near-shore calcareous facies, e.g. Batesford, Maude, Keilor, Flinders, Muddy Cr., Aire R., and in Gippsland in the Glencoe Limestone and Wuk Wuk Marl.

AGE OF THE FYANSFORD CLAY

The clays in the type section of the Fyansford Clay have been correlated by Singleton (1941) with similar clays in the type section of the Balcombian at Balcombe Bay. More recently Carter (1963) has suggested new evidence for the age of these clays, determined from samples from Batesford quarry.

Carter has correlated his Faunal Unit 10 which is represented at Balcombe Bay by 10′ of clays and marls, with the Balcombian stage of Singleton. This unit is represented by 30′ of calcareous clay at Batesford above the highest occurrence of *Lepidocyclina* which continues for 10′ into the clays. The entry of *Orbulina universa* (Faunal Unit 11) corresponds to the beginning of the Bairnsdalian stage as defined by Carter (1959). At Batesford quarry, this interpretation indicates 30′ Balcombian as against 70′ Bairnsdalian (Fig. 16).

When the regional picture is considered in the light of this evidence several difficulties arise.

From the Batesford quarry, a regional dip is known to continue in the clays and underlying limestone as far E. as Coghill's at least. This has the effect of continuously bringing younger beds to the surface towards the E. Some 300′ of clay is known to exist at Coghill's compared to approx. 100′ at the quarry. The upper exposed portion of the section at Coghill's is younger therefore than any part of the clays at the quarry.

The section on Fyansford road appears to be at approximately the same stratigraphic horizon as that at Coghill's. Measurement of dip between these sections is difficult and not very reliable but it is the author's belief that portion of the Fyansford section passes under, and is older than, the uppermost exposed section at Coghill's. In any case, the clays at Fyansford appear in a higher stratigraphic position than the clays immediately overlying the Batesford Limestone. This would mean that both Coghill's and a large part, at least, of the Fyansford sequence would be Bairnsdalian in the sense of Carter. This has been confirmed by the occurrence of Faunal Unit 11 throughout the clay in the Fyansford road cutting (Carter pers. comm.).

The clay at Coghill's and Fyansford road (section 3 and 2) would be regarded therefore as Bairnsdalian on microfaunas and Balcombian on the basis of macrofaunas.

A macrofauna of Bairnsdalian age is known to exist in the sandy limestones and marls of North Shore, Corio Bay (O. P. Singleton pers. comm.).

Even if the regional dip to the E. does not persist to Corio Bay, a considerable thickness of clay must still be accounted for between the Bairnsdalian sediments at North Shore and the base of the Bairnsdalian at Batesford as defined by Carter. Clays and marls are known to occur for 250′ above the disappearance of *Lepidocyclina* in a bore from near Coghill's.

If the Balcombian (Faunal Unit 10) is limited to the same thickness as at the Batesford quarry (Carter 1963), this would assign 220′ to Bairnsdalian against 30′ Balcombian at Coghill's. It would appear therefore that nearly all the clays in the sequence would be Bairnsdalian in the sense of Carter, although some have been correlated with the type section of the Balcombian by F. A. Singleton. Some conflict between macrofaunal and microfaunal evidence therefore is apparent and only detailed palaeontology can resolve the problem.

The Western Beach sequence occupies a stratigraphic position only slightly lower than the North Shore beds, and higher than at least the basal clays exposed in the Fyansford road cutting. Moreover, the Western Beach silty facies is intermediate in composition between the sandy limestone of North Shore and calcareous clays at Fyansford.

Significant differences are apparent between the Western Beach and North Shore faunas, the former being closely related to the gasteropod fauna at Fyansford (as noted also by Mulder 1897). However, the stratigraphic interval separating the basal beds of the Western Beach section and the *Hinnites* limestone bed at North Shore is very small compared to the thickness of clay known to appear near Coghill's in the W.

The faunal differences are therefore to a large extent facies differences rather than age differences alone.

At Coghill's, sandy clays and marls occur with *Hinnites corioensis* which is also recorded from a similar shallow water sequence at Clay Point (Hall and Pritchard 1891). These outcrops are regarded therefore as approximate equivalents and suggest a correlation with the top of the Fyansford section. They may eventually prove to be younger than this, and perhaps should be correlated with sediments on Corio Bay.

The writer's interpretation of the stratigraphic relationships of clays in the various localities is presented diagrammatically in Fig. 18. This interpretation is arrived at from a consideration of regional structure and partly by correlating the sandy facies of the clays with the upper part of the sequence, a limited and local correlation which is thought to reflect slightly stronger currents and coarser detritus associated with the slow in-filling of the basin.

VIADUCT SANDS

The stratigraphic break which occurs at the base of the Viaduct Sands is thought to be diachronous, so that erosion commenced earlier in the near-shore areas than in off-shore regions. Thus the sands immediately overlying the disconformity may be expected to be older in the N. and progressively younger to the S. This is supported by the evidence available, and is illustrated in Fig. 15.

The very widespread continuity of this stratigraphic break in the region of the Upper Miocene is a feature of almost the entire Western Victorian sequence. A nodule bed with disconformity occurs at Beaumaris, the numerous localities in the Geelong area and as far W. as Muddy Cr. near Hamilton (Gill 1957). The cause of this break may be due to either eustatic fall in late Tertiary sea level with consequent submarine erosion, or widespread epeirogenic uplift.

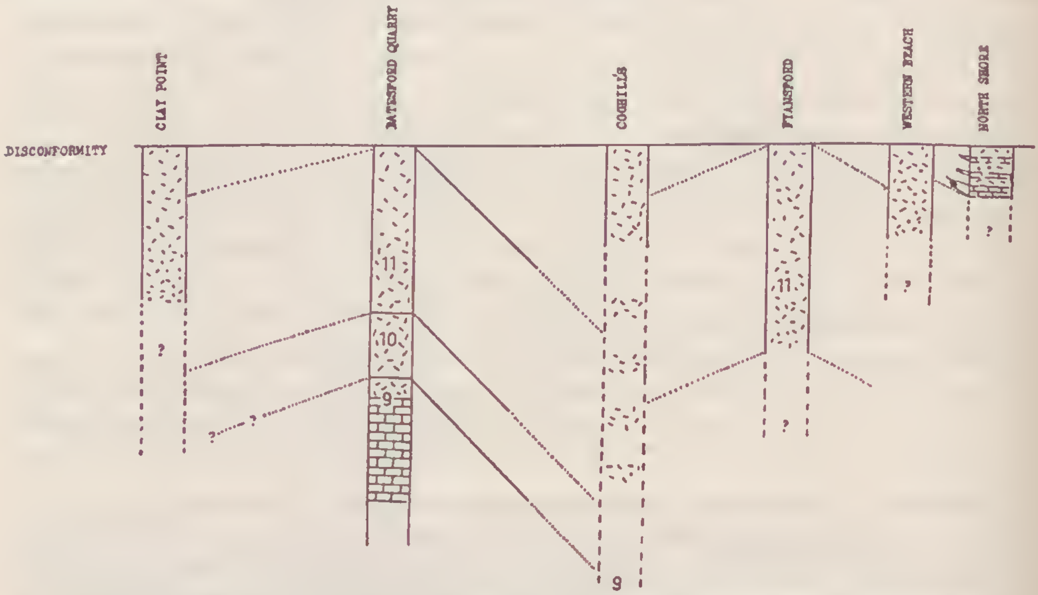


Fig. 18—Illustration of tentative stratigraphic correlation of the various outcrops of Fyansford Clay near Geelong. This interpretetion is based on regional structure, facies variations in the clays and the presence of microfaunal units as shown. Those recorded at Batesford and Fyansford have been described by Carter (1963) whilst the author has observed Faunal Unit 9 at the base of the sequence at Coghill's.

The sands mark the final stage of deposition in a regressive sea. The lithological change from a predominantly clay lithology to a high percentage of coarse detrital quartz sands indicates a change in the strength of the depositional currents accompanied by a change in grain size of the material supplied to the basin.

The influx of coarse material is interpreted as being due to uplift and the initiation of more vigorous erosion in the Central Victorian region represented locally by uplift of the Ordovician plateau N. of Steiglitz. Activity along the E.-W. warp N. of Maude could have the double effect of producing the retreat of the sea from the basin and increasing the rate of supply of quartz sands which had remained on the peneplained land area during the prolonged elluviation in Lower and Middle Tertiary.

The explanation of the occurrence of Werrikooian sediments at the Viaduct, and at that locality alone, cannot at present be provided. The evidence of lithologies, faunal content and secondary alteration, all suggest a considerable time gap (or disconformity) between these and sands of Kalimnan age at the same locality. This suggests a late minor incursion of the sea during Upper Pliocene or early Pleistocene. But there is a complete absence of similar sediments in any outcrop locality to link the Werrikooian at the Viaduct with other evidence of marine incursion.

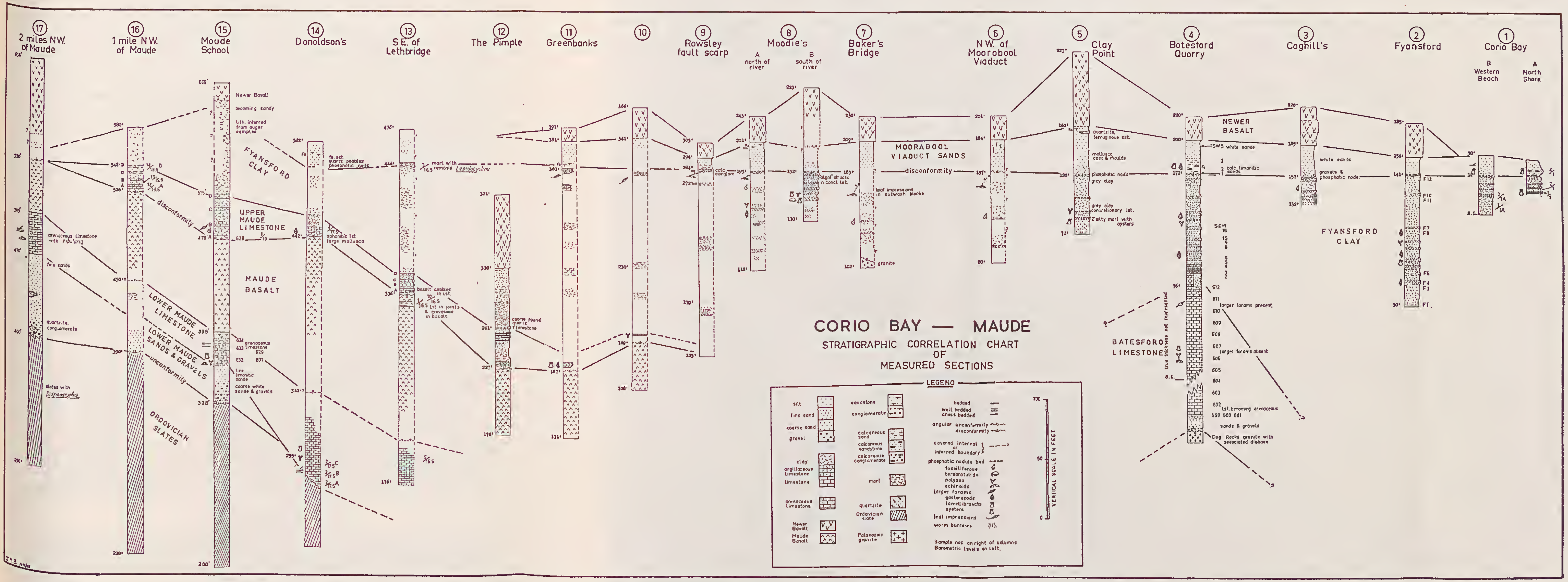


Fig. 19—Detailed stratigraphic section and correlation chart showing location of samples mentioned in text with approximate levels measured by aneroid barometer and checked against known levels. For location of sections see geological map Fig. 1.

Conclusions and Palaeogeographic Summary

From considerations of stratigraphy and depositional environments, the Tertiary sequence is seen to represent a complete cycle of marine deposition with major transgressive and regressive phases clearly represented.

The discovery in recent years of marine Cretaceous sediments in bores in Western Victoria lends weight to the theory that a previous transgression commenced in pre-Tertiary time. In Janjukian time the sea advanced across the shelf from the SW., reaching its most northerly limit at Maude with the deposition of the Lower Maude Formation.

There then followed a long period of deposition through the Miocene with slow accumulation of shallow water limestone and clays at Maude and Geelong. During this period, several regressive and transgressive phases have been recognized. A minor regression occurred after the deposition of the Lower Maude Limestone corresponding to the extrusion of the Maude Basalt. This was followed by minor transgression across the basalt surface, eroding it and disconformably depositing Upper Maude Limestone. Near Geelong this transgression is evident in the upper portion of the Batesford Limestone.

This period culminated in the development of deepest water in the basin in which the clay sequence of Fyansford and Maude was deposited. This is thought to have resulted from a down-warping along the margins of the basin, which resulted in relatively deep water, but maintained low topographic relief throughout the area to the N., and prevented further transgressive on-lap.

Deposition continued with gradual infilling of the basin and progressive coarsening in the sediments until late in the Miocene when the regressive phase commenced probably due to widespread epeirogenic uplift. With shallowing of the sea, large quantities of sediment were eroded and redeposited off-shore in deeper water. This resulted in the excavation of phosphatic concretions and the accumulation of the nodule bed.

Near shoreline at Shelford, the age of the disconformity appears to be pre-Cheltenhamian as at Beaumaris, while in the off-shore region at Geelong, erosion appears to have been taking place during Cheltenhamian time as this is the only stage at present not recognized in the sequence. This suggests that uplift commenced in pre-Cheltenhamian time or Upper Miocene.

This was followed by the deposition of widespread shallow water sands in the Pliocene. A minor marine incursion appears to have occurred in late Pliocene or early Pleistocene.

The final retreat of the sea was followed soon after by the outpouring of the lavas of Newer Basalts which continued intermittently throughout the Pleistocene.

The principal stratigraphic units and their places in the cycle of deposition are summarized in Table 18.

Acknowledgements

Grateful acknowledgement is due to many people for the assistance offered during the completion of this work which was carried out in the Department of Geology in the University of Melbourne as part of the requirements for the degree of Master of Science.

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